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Date: 16 June 1970

RESEARCH PROJECT INITIATION

Project Title: Fluid Measurement

Project No.. B-1145

Project Director: Dr. Ward O. Winer

Sponsor: NASA - Lewis Research Center, Cleveland, Ohio

Agreement Period: From 9 June 1970 until 24 July 1970

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21000 Brookpark Road
Cleveland, Ohio 44135

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Date: February 19, 1971

Project Title: Fluid Measurement

Project No: B-1145

Principal Investigator: Dr. Ward O. Winer

Sponsor: NASA-Lewis Research Center

Effective Termination Date: 9-24-70*

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SCHOOL OF MECHANICAL ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA

FLUID MEASUREMENTS

CONTRACT NO. NAS 3-14546

By

WARD O. WINER

For

NASA-LEWIS RESEARCH CENTER
21000 Brookpark Road
Cleveland, Ohio 44135

24 September 1970

SCHOOL OF MECHANICAL ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

REPORT TO

NASA-LEWIS RESEARCH CENTER
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

SUBJECT

FLUID MEASUREMENTS
CONTRACT NO. NAS 3-14546

SUBMITTED BY

W. O. Winer
Associate Professor
24 September 1970

SUMMARY

This report consists of data on the pressure-viscosity, traction and film thickness behavior of four fluids submitted by NASA-Lewis.

FLUIDS

The four fluids investigated were designated by NASA-Lewis as DN-600 (polyalkyl aromatic), FN-2961 (superrefined paraffinic mineral oil), MCS-418 (modified polyphenyl ether) and MCS-460 (synthetic hydrocarbon). Table 1 contains data supplied by NASA-Lewis with the fluids and the refracture index determined at atmospheric pressure and 77F in an Abbe refractometer in this laboratory.

MEASUREMENTS

Viscosity: Viscosity determinations were made in the equipment and by the methods described in "Some Measurements of High Pressure Lubricant Rheology", Transactions of ASME, Journal of Lubrication Technology, Vol. 90, July 1968, pp. 580-591, by J. D. Novak and W. O. Winer. The apparatus is a pressurized capillary type viscometer. The viscosity determinations fall into two categories. In the first category, the fluid behavior is well defined and is easily interpreted in terms of viscosity as a function of pressure, temperature and shear stress. These data extend from atmospheric pressure to some specific elevated pressure for each fluid and are plotted both as isobars on ASTM viscosity-temperature charts (Figures 1 - 4) as isotherms

on semilog viscosity pressure charts Figures 5 - 8. Also in this category are the data of viscosity as a function of shear stress at 100F and approximately 10,000 psi shown in Figures 9 - 12. The data used for plotting Figures 1 - 12 are also tabulated in Tables 2 - 5. Table 6 contains the initial viscosity-pressure coefficient at atmospheric pressure for each fluid.

The second catagory consists of data above some transition pressure which is specific to the fluid and the temperature. These data were not repeatable within the usual accuracy of the equipment and were characteristic of an irreversible phenomena occurring in the fluid while at that pressure and temperature. The equipment transducer signal response was also different in that the pressure transducer signal lagged the displacement transducer signal by 1/2 to 3 seconds. This compares to the response of these signals being within 10 milliseconds of each other at lower pressures. The apparent viscosity obtained under these conditions was invariably greater than the value expected from the extrapolation of the isotherm from the lower pressure data. Although not well defined, there was a tendency for this apparent viscosity to decrease toward the extrapolated valve as the same sample was passed through the capillary repeatedly. This type of behavior suggests the possibility of the existance of a solid phase forming from some of the high molecular weight constitutents at these pressures and temperatures which is then broken down mechanically as energy is dissipated in the fluid by repeated passes through the capillary. This mechanical degradation is reflected as a decrease in the apparent viscosity. Data in this category is tabulated in Tables 2 - 5 and is marked with an asterisk. It is not plotted. Table 7

contains the pressures at which this behavior was first observed while increasing pressure and the approximate time delay of the differential pressure signals behind the displacment signal.

Traction and Film Thickness: Traction and film thickness determinations were made in the equipment and by the methods described in "Fluid Rheological Effects in Sliding Elastohydrodynamic Point Contacts with Transient Loading: I-Film Thickness and II-Traction", ASME Paper 70-LUB-21 & 22 by D. M. Sanborn and W. O. Winer. This apparatus consists of a rotating steel ball loaded against a sapphire plate. Data were taken at several loads and speeds, and at room temperature which was 72F. For three of the fluids the mean Hertz pressures ranged both above and below the transition pressure discussed in the previous section. However for MCS-460 the transition pressure was less than 30 psi and all the traction and film thickness data are for mean Hertz pressure values greater than 30 kpsi because the apparatus as it currently exists does not permit accurate data to be taken at such low loads. The film thickness and traction data are well behaved at mean Hertz pressures both above and below the transition pressure observed in the viscometer and show a smooth behavior across that pressure.

The film thickness data are tabulated in Table 8 and the traction data in Table 9. The traction data tablulated in Table 9 are values taken at specified loads from the curves plottted.

In the film thickness determinations white tungsten light is used after passing it through a narrow band pass filter with peak intensity at 5340 $\mathring{A}$ wavelength. The experimentally determined phase shift of the reflected light with zero film thickness in the presence of each fluid was $5\pi/4$.

Figures 13 and 14 show the centerline and minimum film thicknesses respectively as a function of sliding speed for high (15 lbf) and low (2 lbf) loads. The cross hatched bands in Figure 13 represent the 90% confidence level of the centerline film thickness data. Figures 15 - 18 A contain the film thickness profiles at 13.7 ips sliding speed and the highest load (15 lbf). The circles represent a section along the centerline from entrance to exit and the triangles a section along a radius from the contact center through the minimum film thickness. Figures 15 - 18 B are identical to Figures 15 - 18 A except the load is the lowest load (2 lbf). Above the graph in each of these figures is a photograph of the film thickness interference pattern from which the data was plotted (the original photographs are attached to the original copy of the report). Figure 19 is a photograph of a stage micrometer where each small division is 1 x 10 inches to show the scale in the interference pattern photographs.

Figures 20 and 21 show the traction coefficient data as a function of load and sliding speed.

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LIST OF FIGURES

TABLE 1

DESCRIPTION AND PROPERTIES OF EXPERIMENTAL FLUIDS

Fluid	DN-600	EN-2961	MCS-418	MCS-460
Chemical Type	Polyalkyl Aromatic	Superrefined Paraffinic Mineral Oil	Modified Polyphenyl Ether	Synthetic Hydrocarbon
Viscosity, cs				
-40°F	9,700	---	---	---
0°F	---	10,300	13,040	26,075
100°F	30	78	25	37.2
210°F	5.0	8.2	4.1	4.0
300°F	2.3	3.3	2.0	1.9
Pour Point, °F	- 75	-30	-20	-20 to -25
Density, g/ml				
0°F	.884	.908	---	0.9595
77°F	---	---	1.195	0.9327
100°F	.851	.873	1.184	0.9219
300°F	.783	.803	1.101	0.8504
Refractive Index (atm pressure 77F, White Tungsten Light)	1.4824	1.4787	1.67345	1.5044

Table 2 : FLUID JN-600

TEMP. (DEG.F)	PRESS. (PSIG)	DENSITY (GM/CC)	VISCOSITY (POISE)	SHEAR STRESS (DYNE/SQ.CM.)	SHEAR RATE (1/SEC.)	CAP. NO.
100	4951.4	.851	.599	4358.2	7277.2	4
100	4951.4	.851	.629	2934.5	4662.0	4
100	4951.4	.851	.629	9441.3	15009.3	4
100	4951.4	.851	.566	10842.7	19148.2	4
100	10794.5	.851	1.326	2723.7	2054.3	4
100	10794.5	.851	1.156	7230.4	6252.1	4
100	10794.5	.851	1.115	4232.9	3795.9	4
100	10794.5	.851	1.203	12572.7	10449.9	4
100	10794.5	.851	1.383	4816.0	3483.3	4
100	10794.5	.851	1.285	14346.4	11164.4	4
100	23184.4	.851	4.171	4856.0	1164.2	4
100	23184.4	.851	4.009	7787.8	1942.4	4
100	23184.4	.851	4.319	3360.7	778.2	4
100	23184.4	.851	4.233	11489.3	2714.4	4
100	23184.4	.851	4.328	9340.6	2158.2	4
100	32405.3	.851	7.739	10599.8	1369.6	4
100	32405.3	.851	7.577	6250.4	824.9	4
100	32385.8	.851	7.426	12483.1	1680.9	4
100	32385.8	.851	7.719	7496.8	971.2	4
100	32385.8	.851	7.436	12530.1	1685.1	4
100	38175.4	.851	14.311	11826.6	826.4	4
100	38175.4	.851	12.400	16776.0	1352.9	4
100	38175.4	.851	13.199	13722.0	1039.6	4
100	38175.4	.851	13.537	16839.8	1244.0	4
100	38175.4	.851	13.524	6695.4	495.1	4
100	48422.0	.851	31.185	10756.6	344.9	4
100	48422.0	.851	28.100	10348.0	368.3	4
100	48422.0	.851	33.111	24752.2	747.6	4
100	48422.0	.851	31.650	23310.3	736.5	4
100	48422.0	.851	33.566	8978.6	267.5	4
100	60651.2	.851	61.224	18744.3	306.2	4
100	60651.2	.851	84.787	33503.3	395.1	4
100	60651.2	.851	93.848	45971.7	489.9	4
100	60651.2	.851	82.252	37773.0	459.2	4
100	60651.2	.851	82.862	33994.1	410.2	4
100	70786.0	.851	154.515	18477.1	119.6	4
100	70786.0	.851	144.202	15519.5	107.6	4
100	70786.0	.851	152.761	34251.3	224.2	4
100	70786.0	.851	148.269	26994.1	182.1	4
100	70786.0	.851	179.903	33022.5	183.6	4
100	79020.6	.851	238.553	22821.1	95.7	4
100	79020.6	.851	241.569	25926.2	107.3	4
100	79020.6	.851	334.240	31209.0	93.4	4
100	79020.6	.851	285.432	30719.0	107.6	4

Table 2 : [illegible] cont.

TEMP. (DEG.F)	PRESS. (PSIG)	DENSITY (GM/CC)	VISCOSITY (POISE)	SHEAR STRESS (DYNE/SQ.CM.)	SHEAR RATE (1/SEC.)	CAP. NO.
100	11161.[illegible]	.851	1.[illegible]10	601158.0	629167.[illegible]	1
100	11161.[illegible]	.851	.[illegible]04	770379.3	852312.[illegible]	1
100	11044.[illegible]	.851	.[illegible]07	956998.5	1186344.[illegible]	1
100	11605.[illegible]	.851	.[illegible]20	917548.2	1119265.5	1
100	11395.[illegible]	.851	.[illegible]76	878809.5	1000432.[illegible]	1
100	11605.[illegible]	.851	1.[illegible]87	104871.9	151407.[illegible]	1
100	11391.[illegible]	.851	1.[illegible]00	917607.9	655300.[illegible]	1
100	1 156.[illegible]	.851	1.[illegible]32	115489.6	93721.[illegible]	1
100	1.058.[illegible]	.851	1.[illegible]97	378402.3	308430.[illegible]	1
100	1 156.[illegible]	.851	.767	1065576.8	1390180.[illegible]	1
100	1.314.[illegible]	.851	.[illegible]67	1009557.2	1042951.[illegible]	1
100	11262.[illegible]	.851	.[illegible]26	979974.5	1014594.[illegible]	1
100	95424.[illegible]	.851	714.365	317642.6	444.7	1
100	95424.[illegible]	.851	736.[illegible]33	340434.5	467.5	1
100	95424.[illegible]	.851	781.767	405536.1	518.5	1
100	95749.[illegible]	.851	702.[illegible]77	426724.3	607.6	1
100	95912.[illegible]	.851	738.900	272425.7	368.7	1
100	95261.7	.851	614.[illegible]7[illegible]	266628.6	527.[illegible]	1
100	10 871.[illegible]	.851	972.[illegible]98	304036.2	594.7	1
100	10.871.[illegible]	.851	1172.[illegible]57	567966.1	569.[illegible]	1
100	10.871.[illegible]	.851	1237.[illegible]39	636614.5	514.[illegible]	1
100	10 871.[illegible]	.851	1262.[illegible]20	714530.2	566.1	1
100	10.871.[illegible]	.851	1214.[illegible]3[illegible]	1058681.[illegible]	871.[illegible]	1
100	9[illegible]96.7	.851	1133.[illegible]8[illegible]	1407106.3	1311.7	1
100	9[illegible]98.7	.851	1106.[illegible]07	1554300.9	1404.[illegible]	1
100	10 860.[illegible]	.851	1262.[illegible]75	1006350.[illegible]	868.2	1
100	9[illegible]98.7	.851	953.[illegible]5[illegible]	204201.[illegible]	214.1	1
100	9[illegible]898.7	.851	1224.[illegible]10	228718.9	186.[illegible]	1
100	101[illegible]96.[illegible]	.851	1274.[illegible]9[illegible]	1117719.9	877.[illegible]	1

Table 2: FLUID SN-600 cont.

TEMP. (DEG.F)	PRESS. (PSIG)	DENSITY (GM/CC)	VISCOSITY (POISE)	SHEAR STRESS (DYNE/SQ.CM.)	SHEAR RATE (1/SEC.)	CAP. NO.
210	4939.5	.815	.[illegible]	1827.6	21565.1	4
210	4939.5	.815	.093	3272.5	35136.7	4
210	4939.5	.815	.086	1910.2	21624.8	4
210	4939.5	.815	.[illegible]9[illegible]	4246.2	43249.6	4
210	4939.5	.815	.098	3629.7	37052.2	4
210	10490.5	.815	.162	2169.0	13383.6	4
210	10404.6	.815	.152	5264.4	35008.4	4
210	10404.6	.815	.145	5062.1	35008.4	4
210	10404.6	.815	.158	3246.1	21097.1	4
210	10404.6	.815	.153	5503.9	34722.7	4
210	19807.5	.815	.296	4673.9	15798.8	4
210	19807.5	.815	.293	3064.1	7783.8	4
210	19807.5	.815	.321	2201.8	6864.9	4
210	19807.5	.815	.306	3205.9	10484.4	4
210	19807.5	.815	.297	6123.2	20594.7	4
210	34149.5	.815	.[illegible]45	2620.0	4062.0	4
210	34149.5	.815	.550	5835.9	10459.9	4
210	34149.5	.815	.575	6001.9	10446.1	4
210	34149.5	.815	.566	3945.5	6966.1	4
210	34184.2	.815	.947	8623.2	9108.0	4
210	34184.2	.815	1.005	5466.5	5441.5	4
210	34184.2	.815	.989	4098.7	4145.9	4
210	34184.2	.815	1.057	4618.1	4368.7	4
210	44901.5	.815	1.619	8810.4	5441.5	4
210	44901.5	.815	1.579	6814.4	4319.6	4
210	44901.5	.815	1.577	8905.1	5561.7	4
210	44901.5	.815	1.[illegible]59	8349.5	5052.8	4
210	64686.5	.815	3.[illegible]49	8719.0	2859.6	4
210	64686.5	.815	3.314	15451.2	4662.4	4
210	64686.5	.815	3.[illegible]95	15624.8	5047.8	4
210	63691.7	.815	3.129	15101.5	4857.5	4
210	64023.5	.815	3.171	17564.3	5538.5	4
210	74157.5	.815	4.746	18235.9	3841.8	4
210	74157.5	.815	4.[illegible]97	12380.6	2635.5	4
210	73971.5	.815	4.[illegible]11	13567.8	2762.9	4
210	73971.5	.815	4.[illegible]92	19661.8	4089.1	4
210	73971.5	.815	4.752	15036.5	3161.5	4
210	63874.5	.815	6.[illegible]83	22934.0	3481.2	4
210	73609.5	.815	5.068	20389.3	3413.1	4
210	63597.9	.815	6.772	8959.5	1325.2	4
210	63597.9	.815	6.[illegible]52	9749.5	1442.9	4

Table 2: [illegible] cont.

TEMP. (DEG.F)	PRESS. (PSIG)	DENSITY (GM/CC)	VISCOSITY (POISE)	SHEAR STRESS (DYNE/SQ.CM.)	SHEAR RATE (1/SEC.)	CAP. NO.
300	4980.3	.783	.043	3405.0	78733.8	4
300	4980.3	.783	.040	1837.3	45372.0	4
300	4980.3	.783	.035	721.1	20461.9	4
300	4947.1	.783	.038	1157.6	30425.9	4
300	4980.3	.783	.037	1527.2	40775.5	4
300	10267.1	.783	.052	1581.4	30396.3	4
300	10267.1	.783	.054	1710.3	31434.2	4
300	10267.1	.783	.052	843.0	16263.9	4
300	10345.5	.783	.055	1111.6	20039.3	4
300	10423.9	.783	.062	1908.5	30814.1	4
300	19178.4	.783	.093	1251.0	13432.9	4
300	19116.5	.783	.090	1191.7	13296.6	4
300	19054.6	.783	.091	1180.8	12938.1	4
300	18992.7	.783	.095	1605.7	16910.5	4
300	29001.5	.783	.154	1065.5	6923.6	4
300	29001.5	.783	.145	1115.1	7671.1	4
300	29001.5	.783	.147	1188.3	8073.8	4
300	29001.5	.783	.162	1823.8	11257.9	4
300	29001.5	.783	.156	1127.4	7249.4	4
300	39841.1	.783	.273	1818.3	6531.9	4
300	39683.5	.783	.249	2306.7	9254.9	4
300	39841.1	.783	.276	2402.9	8709.2	4
300	39841.1	.783	.273	2385.5	8746.0	4
300	39526.0	.783	.294	2290.3	7802.4	4
300	50100.4	.783	.439	3445.1	7848.4	4
300	49940.1	.783	.386	2205.2	5710.5	4
300	49940.1	.783	.408	1699.7	4165.9	4
300	49940.1	.783	.260	1323.8	5091.6	4
300	50100.4	.783	.421	2314.3	5500.8	4
300	61019.7	.783	.606	3124.7	5155.6	4
300	61019.7	.783	.635	1875.5	2953.7	4
300	61019.7	.783	.623	2196.6	3526.4	4
300	61019.7	.783	.647	1362.6	2105.3	4
300	61019.7	.783	.665	815.0	1225.6	4
300	72582.2	.783	.840	3350.7	3987.5	4
300	72582.2	.783	.982	3249.8	3310.7	4
300	72582.2	.783	.984	2863.5	2911.5	4
300	72745.0	.783	.909	3577.3	3936.9	4
300	84585.5	.783	1.393	4870.2	3497.0	4
300	84585.5	.783	1.439	6248.1	4341.9	4
300	84101.9	.783	1.495	5443.0	3641.8	4
300	84101.9	.783	1.397	4917.8	3521.4	4
300	84101.9	.783	1.429	4012.3	2807.9	4
300	84585.5	.783	1.625	5854.3	3602.9	4

Table 3 : FLUID FN-2961

TEMP. (DEG.F)	PRESS. (PSIG)	DENSITY (GM/CC)	VISCOSITY (POISE)	SHEAR STRESS (DYNE/SQ.CM.)	SHEAR RATE (1/SEC.)	CAP. NO
100	4994.4	.873	2.033	5047.5	2482.3	4
100	4994.4	.873	2.120	7123.2	3359.6	4
100	4994.4	.873	2.230	7939.4	3561.0	4
100	4994.4	.873	2.082	4887.1	2347.5	4
100	4994.4	.873	2.104	8729.2	4148.1	4
100	10660.3	.873	7.027	9967.4	1418.5	4
100	10660.3	.873	6.320	8197.6	1297.2	4
100	10660.3	.873	6.648	16660.7	2506.2	4
100	10660.3	.873	6.382	7564.2	1185.2	4
100	10660.3	.873	6.532	7363.9	1127.3	4
100	10660.3	.873	6.545	21426.3	3273.6	4
100	19443.2	.873	24.534	9873.9	402.5	4
100	19443.2	.873	23.353	11358.7	486.4	4
100	19443.2	.873	23.280	18320.5	787.0	4
100	19443.2	.873	24.148	7646.8	316.7	4
100	29840.6	.873	93.472	27620.2	295.5	4
100	29840.6	.873	99.400	38159.9	383.9	4
100	29840.6	.873	88.269	16275.6	184.4	4
100	29840.6	.873	92.859	23131.2	249.1	4
100	29840.6	.873	89.485	41302.6	461.6	4
100	*39933.8	.873	295.218	38587.5	130.7	4
100	*39933.8	.873	304.648	29865.1	98.0	4
100	*39933.8	.873	328.274	31573.4	96.2	4
100	*49528.6	.873	993.392	48082.7	48.4	4
100	*49528.6	.873	2149.467	45068.4	21.0	4
100	*49528.6	.873	1246.079	33707.2	27.1	4
100	*49528.6	.873	742.295	30092.5	40.5	4

Table 3: [illegible] cont.

TEMP. (DEG.F)	PRESS. (PSIG)	DENSITY (GM/CC)	VISCOSITY (POISE)	SHEAR STRESS (DYNE/SQ.CM.)	SHEAR RATE (1/SEC.)	CAP. NO.
100	11108.[illegible]	.875	6.[illegible]	92999.3	14553.0	1
100	11627.[illegible]	.875	5.[illegible]	708639.0	131356.4	1
100	11509.[illegible]	.875	4.[illegible]	992458.6	192985.9	1
100	9732.	.875	4.611	1067770.5	236714.2	1
100	11516.[illegible]	.875	6.[illegible]	607572.6	140581.3	1
100	11130.[illegible]	.875	4.[illegible]	837560.5	177794.1	1
100	11500.[illegible]	.875	3.[illegible]	1794657.1	481284.0	1
100	11108.[illegible]	.875	5.725	351084.2	61329.0	1
100	11106.[illegible]	.875	5.[illegible]	362824.0	61329.0	1
100	10937.[illegible]	.875	6.[illegible]	313297.3	51516.3	1
100	10947.[illegible]	.875	5.[illegible]	208796.1	49943.4	1
100	*40841.[illegible]	.875	416.[illegible]	50055.1	129.3	1
100	*40841.[illegible]	.875	332.[illegible]	139734.5	589.7	1
100	*40862.[illegible]	.875	272.152	195010.7	679.8	1
100	*40862.[illegible]	.875	256.[illegible]	253112.8	985.2	1
100	*51326.[illegible]	.875	686.[illegible]	1177292.4	2819.2	1
100	*51326.[illegible]	.875	741.[illegible]	1560800.3	2104.1	1
100	*51837.[illegible]	.875	735.[illegible]	1154315.6	1568.6	1
100	*51837.[illegible]	.875	748.[illegible]	1619213.0	2163.4	1
100	*53826.[illegible]	.875	3537.[illegible]	759896.2	193.0	1
100	*57092.[illegible]	.875	1967.[illegible]	845073.0	429.5	1
100	*57092.[illegible]	.875	2079.[illegible]	718038.6	345.5	1
100	*57626.	.875	3630.147	708694.8	252.5	1
100	*53549.[illegible]	.875	1974.[illegible]	852540.4	447.0	1
100	*53825.[illegible]	.875	2299.[illegible]	1159627.2	504.5	1
100	*53826.[illegible]	.875	2091.[illegible]	1009742.5	482.2	1
100	*53102.[illegible]	.875	2439.[illegible]	932745.5	382.4	1
100	*50750.[illegible]	.875	2081.[illegible]	1434183.4	689.2	1

Table 3 : FLUID FN-2961 cont.

TEMP. (DEG.F)	PRESS. (PSIG)	DENSITY (GM/CC)	VISCOSITY (POISE)	SHEAR STRESS (DYNE/SQ.CM.)	SHEAR RATE (1/SEC.)	CAP. NO.
210	5010.9	.836	.143	1279.7	8953.5	4
210	5027.4	.836	.158	915.5	5808.9	4
210	5047.1	.836	.138	1566.9	11370.0	4
210	5043.8	.836	.152	1475.9	9681.6	4
210	5043.8	.836	.153	1552.0	10161.8	4
210	10926.9	.836	.323	2246.7	6960.4	4
210	10926.9	.836	.330	5747.2	17395.5	4
210	10991.8	.836	.343	5412.8	15789.8	4
210	10991.8	.836	.340	1917.4	5636.1	4
210	10991.8	.836	.355	5332.3	15029.6	4
210	20958.2	.836	.866	5617.2	6489.9	4
210	20958.2	.836	.855	5076.6	5939.4	4
210	20958.2	.836	.891	3296.1	3698.9	4
210	20958.2	.836	.877	3928.9	4477.9	4
210	20837.9	.836	.900	5079.4	5646.5	4
210	31292.6	.836	2.390	7447.0	3116.2	4
210	31142.3	.836	2.334	4989.3	2137.7	4
210	31142.3	.836	2.123	4340.2	2044.2	4
210	31072.1	.836	2.245	3930.8	1751.3	4
210	41819.5	.836	5.115	9212.0	1801.1	4
210	41819.5	.836	5.368	15207.3	2833.1	4
210	41819.5	.836	5.293	23163.1	4375.9	4
210	41819.5	.836	5.526	17633.8	3191.2	4
210	41819.5	.836	5.585	39146.7	7009.3	4
210	52048.7	.836	11.914	26468.6	2221.7	4
210	52048.7	.836	12.252	23222.2	1895.4	4
210	52048.7	.836	13.257	28748.2	2168.5	4
210	52048.7	.836	12.437	20227.2	1626.4	4
210	52048.7	.836	13.459	28219.9	2096.7	4
210	* 60029.6	.836	24.156	26699.8	1105.3	4
210	* 60029.6	.836	22.487	22741.5	1011.3	4
210	* 59867.6	.836	21.009	15935.1	758.5	4
210	* 59867.6	.836	22.542	15650.8	694.3	4

Table 3 : FLUID FN-2961 cont.

TEMP. (DEG.F)	PRESS. (PSIG)	DENSITY (GM/CC)	VISCOSITY (POISE)	SHEAR STRESS (DYNE/SQ.CM.)	SHEAR RATE (1/SEC.)	CAP. NO.
300	5042.1	.803	.056	1460.1	26293.0	4
300	5042.1	.803	.057	1710.8	30220.4	4
300	5042.1	.803	.061	1919.8	31466.9	4
300	5042.1	.803	.056	1657.5	29859.0	4
300	11243.3	.803	.106	2584.7	24376.0	4
300	11243.3	.803	.112	2098.4	18807.9	4
300	11243.3	.803	.127	2117.1	16726.4	4
300	11243.3	.803	.126	1049.1	8340.9	4
300	11243.3	.803	.125	1088.8	8697.7	4
300	20376.8	.803	.231	1252.1	5411.1	4
300	20376.8	.803	.204	1032.1	5064.8	4
300	20376.8	.803	.197	1327.3	6753.1	4
300	20376.8	.803	.190	1477.1	7770.4	4
300	31268.4	.803	.430	2617.8	6091.3	4
300	31268.4	.803	.450	1585.2	3520.8	4
300	31268.4	.803	.490	1181.0	2408.1	4
300	31268.4	.803	.419	1327.8	3171.5	4
300	41875.2	.803	.805	1268.3	1575.2	4
300	41875.2	.803	.820	2112.2	2574.9	4
300	41875.2	.803	.852	2687.2	3154.9	4
300	41875.2	.803	.879	3558.2	4049.1	4
300	42194.3	.803	.928	4075.2	4391.3	4
300	42194.3	.803	.916	4720.7	5151.6	4
300	42194.3	.803	.861	3500.0	4065.0	4
300	42194.3	.803	.897	4083.6	4554.5	4
300	50271.7	.803	1.418	3149.8	2221.7	4
300	50271.7	.803	1.399	3643.5	2603.6	4
300	50271.7	.803	1.432	3957.3	2763.2	4
300	50271.7	.803	1.452	6531.7	4499.0	4
300	50271.7	.803	1.569	4316.1	2751.7	4
300	* 63196.2	.803	2.862	4182.1	1461.5	4
300	* 63196.2	.803	3.008	5054.7	1680.2	4

TEMP. (DEG.F)	PRESS. (PSIG)	DENSITY (GM/CC)	VISCOSITY (POISE)	SHEAR STRESS (DYNE/SQ.CM.)	SHEAR RATE (1/SEC.)	CAP. NO.
100	5042.1	1.184	.800	4547.6	5686.3	4
100	5042.1	1.184	.679	4005.2	5899.7	4
100	5042.1	1.184	.632	4333.8	6860.0	4
100	4990.6	1.184	.646	4603.1	7125.7	4
100	4990.6	1.184	.754	5026.3	6665.4	4
100	9819.7	1.184	1.384	4147.5	2996.4	4
100	9819.7	1.184	1.364	4824.6	3537.4	4
100	9819.7	1.184	1.396	5668.2	4061.1	4
100	9819.7	1.184	1.358	7870.7	5795.2	4
100	2[illegible]353.3	1.184	6.389	12004.8	1878.9	4
100	20353.3	1.184	7.217	10082.7	1397.1	4
100	20353.3	1.184	6.577	9333.4	1419.2	4
100	20353.3	1.184	7.054	7585.6	1075.4	4
100	20353.3	1.184	6.961	9917.4	1424.7	4
100	28980.0	1.184	31.402	10915.3	347.6	4
100	28980.0	1.184	29.679	21734.5	732.3	4
100	28980.0	1.184	31.518	20772.7	659.1	4
100	29150.5	1.184	28.318	34797.4	1228.8	4
100	* 39713.3	1.184	341.261	33529.6	98.3	4
100	* 39713.3	1.184	237.483	26525.8	111.7	4
100	* 39713.3	1.184	348.126	36544.2	105.0	4
100	* 39713.3	1.184	211.637	29298.9	138.4	4
100	* 39713.3	1.184	291.733	26702.4	91.5	4
100	1[illegible]701.3	1.184	1.[illegible]23	129517.9	67354.3	1
100	9645.5	1.184	1.746	92082.6	52735.1	1
100	9645.5	1.184	1.[illegible]44	130890.2	79606.2	1
100	9608.1	1.184	1.[illegible]80	175420.5	85723.7	1
100	10790.2	1.184	1.[illegible]56	118335.8	60496.6	1
100	10657.[illegible]	1.184	1.[illegible]85	203921.1	155935.[illegible]	1
100	10525.6	1.184	1.[illegible]93	306200.0	541283.6	1
100	10348.1	1.184	1.[illegible]61	959239.5	656599.3	1
100	10259.7	1.184	1.[illegible]97	825482.5	619652.6	1
100	1[illegible]480.[illegible]	1.184	1.717	543326.6	317377.5	1
100	* 4[illegible]161.[illegible]	1.184	615.[illegible]59	409422.2	793.5	1
100	* 4[illegible]342.1	1.184	699.797	374476.0	546.0	1
100	* 4[illegible]161.[illegible]	1.184	670.134	746754.6	1114.3	1
100	* 4[illegible]161.[illegible]	1.184	579.[illegible]59	851770.3	1469.5	1
100	* 4[illegible]342.[illegible]	1.184	947.[illegible]50	635332.6	723.7	1
100	* 4[illegible]961.7	1.184	656.130	912968.8	1391.4	1

Table 4 : FLUID MCS-418 cont.

TEMP. (DEG.F)	PRESS. (PSIG)	DENSITY (GM/CC)	VISCOSITY (POISE)	SHEAR STRESS (DYNE/SQ.CM.)	SHEAR RATE (1/SEC.)	CAP. NO.
210	5049.0	1.138	.077	1538.0	19848.2	4
210	5049.0	1.138	.046	581.1	6740.9	4
210	5049.0	1.138	.088	1102.0	12587.1	4
210	5083.3	1.138	.090	1655.6	18475.0	4
210	5083.3	1.138	.093	881.4	9518.4	4
210	10075.1	1.138	.120	1841.5	15368.8	4
210	10075.1	1.138	.122	2165.4	17788.4	4
210	10075.1	1.138	.125	2138.4	17060.3	4
210	10075.1	1.138	.118	1106.1	9362.3	4
210	10075.1	1.138	.123	2617.6	21325.3	4
210	29069.3	1.138	.425	1461.2	3437.9	4
210	29307.4	1.138	.439	2352.7	5373.3	4
210	29108.9	1.138	.429	2067.7	4820.3	4
210	29307.4	1.138	.438	1665.3	3804.0	4
210	29307.4	1.138	.436	2729.3	6264.6	4
210	* 44326.6	1.138	.718	874.9	1218.7	4
210	* 44528.2	1.138	1.153	2363.0	2050.0	4
210	* 44427.7	1.138	.877	2156.1	2457.5	4
210	* 44326.6	1.138	1.604	2620.6	1634.1	4
210	* 44225.5	1.138	1.215	2543.9	2093.3	4
210	* 51921.6	1.138	24.017	3270.2	136.2	4
210	* 51921.6	1.138	14.640	1547.9	105.7	4
210	* 51921.6	1.138	30.650	2859.8	93.3	4
210	* 52243.5	1.138	15.479	1982.8	128.1	4
300	4990.6	1.101	.037	957.5	25356.5	4
300	4990.6	1.101	.039	592.5	15354.2	4
300	4990.6	1.101	.036	795.8	21959.1	4
300	9926.2	1.101	.069	1992.5	28742.4	4
300	9926.2	1.101	.061	1237.4	20285.1	4
300	9926.2	1.101	.057	984.6	17304.7	4
300	9926.2	1.101	.070	1875.3	26807.5	4
300	9926.2	1.101	.076	1931.7	25340.7	4
300	19551.6	1.101	.103	1267.5	12276.3	4
300	19551.6	1.101	.096	1038.9	10812.6	4
300	19551.6	1.101	.089	958.8	10812.6	4
300	28769.3	1.101	.149	844.3	5666.0	4
300	28769.3	1.101	.149	1173.4	7869.4	4
300	28769.3	1.101	.148	2148.4	14479.7	4
300	28769.3	1.101	.138	2586.8	18682.0	4
300	* 43334.2	1.101	.394	670.1	1701.5	4
300	* 43334.2	1.101	.594	1188.0	1998.6	4
300	* 43334.2	1.101	.522	1934.3	3702.5	4
300	* 43334.2	1.101	.221	1052.3	4867.6	4

Table 5: FLUID MCS-460

TEMP. (DEG.F)	PRESS. (PSIG)	DENSITY (GM/CC)	VISCOSITY (POISE)	SHEAR STRESS (DYNE/SQ.CM.)	SHEAR RATE (1/SEC.)	CAP. NO.
100	5053.9	.922	1.199	5019.2	4187.4	4
100	5003.2	.922	1.267	4038.9	3188.4	4
100	5037.0	.922	1.217	4288.4	3523.2	4
100	5037.0	.922	1.517	4945.3	3259.2	4
100	10766.1	.922	6.787	8255.8	1216.5	4
100	10806.0	.922	6.869	7659.0	1115.0	4
100	11125.4	.922	7.129	15638.7	2193.8	4
100	11125.4	.922	7.265	20567.8	2831.0	4
100	10585.9	.922	6.189	1749.1	282.6	4
100	18749.4	.922	74.578	15107.2	202.6	4
100	18461.2	.922	63.661	8119.1	127.5	4
100	18461.2	.922	68.168	10328.3	151.5	4
100	19574.6	.922	55.278	15095.3	273.1	4
100	19574.2	.922	60.351	22022.2	364.9	4
100	1[illegible]814.	.922	4.796	376293.5	57623.8	1
100	1[illegible]739.	.922	4.[illegible]56	371431.7	79812.5	1
100	1[illegible]814.	.922	4.793	431817.0	87926.0	1
100	1[illegible]701.7	.922	4.529	400482.8	108293.1	1
100	11207.	.922	5.736	292707.9	35529.4	1
100	11207.	.922	5.[illegible]7[illegible]	151592.5	21676.5	1
100	1[illegible]493.1	.922	2.[illegible]97	1570950.4	542104.4	1
100	1[illegible]692.5	.922	4.[illegible]67[illegible]	295401.9	60985.9	1
100	11191.[illegible]	.922	2.[illegible]29	1419848.6	596162.4	1
100	11794.[illegible]	.922	1.[illegible]49	1557325.5	1143707.4	1
100	11116.[illegible]	.922	2.[illegible]4[illegible]	1503984.1	738408.8	1
100	11696.[illegible]	.922	2.227	1701521.9	804509.0	1
100	1[illegible]356.[illegible]	.922	55.[illegible]31	530245.8	15156.5	1
100	1[illegible]142.[illegible]	.922	55.[illegible]23	672059.8	19200.4	1
100	1[illegible]142.	.922	57.[illegible]21	1001725.8	26416.4	1
100	1[illegible]821.[illegible]	.922	58.[illegible]73	916866.4	24399.3	1
100	1[illegible]821.[illegible]	.922	39.[illegible]7[illegible]	1009551.9	57303.6	1
100	1[illegible]356.	.922	43.[illegible]1[illegible]	600388.5	13672.4	1
100	1[illegible]356.[illegible]	.922	46.[illegible]54	208385.8	6554.6	1
100	*[illegible]489.1	.922	1129.[illegible]95	743579.7	722.1	1
100	*[illegible]489.[illegible]	.922	1053.[illegible]43	525727.6	496.8	1
100	*[illegible]834.[illegible]	.922	612.[illegible]45	307256.6	651.8	1
100	*[illegible]956.7	.922	1142.[illegible]93	937351.1	820.5	1
100	*[illegible]304.[illegible]	.922	989.[illegible]7[illegible]	622873.8	645.5	1

Table 5 : FLUID MCS-460 cont.

TEMP. (DEG.F)	PRESS. (PSIG)	DENSITY (GM/CC)	VISCOSITY (POISE)	SHEAR STRESS (DYNE/SQ.CM.)	SHEAR RATE (1/SEC.)	CAP. NO.
210	5079.9	.882	.078	1527.9	19511.4	4
210	5079.9	.882	.076	1450.3	19053.5	4
210	5079.9	.882	.071	1299.6	18364.5	4
210	5079.9	.882	.065	1100.9	16874.7	4
210	10659.2	.882	.163	1475.1	9078.6	4
210	10659.2	.882	.175	1270.3	7267.3	4
210	10659.2	.882	.164	1128.7	6882.3	4
210	10659.2	.882	.164	1067.1	6492.7	4
210	10698.4	.882	.180	1878.7	10425.4	4
210	19045.0	.882	.515	2942.7	5711.2	4
210	18996.5	.882	.521	1407.7	2702.4	4
210	16996.5	.882	.541	1808.1	3343.3	4
210	19045.0	.882	.501	2484.3	4963.1	4
210	19045.0	.882	.496	1789.7	3611.4	4
210	19045.0	.882	.503	3369.6	6701.7	4
300	5079.9	.850	.030	1989.9	65722.7	4
300	5079.9	.850	.031	878.9	28246.3	4
300	5079.9	.850	.031	2209.6	70726.9	4
300	5079.9	.850	.032	2108.6	66723.5	4
300	5079.9	.850	.034	2278.1	66723.5	4
300	19574.2	.850	.114	1839.8	16097.2	4
300	19574.2	.850	.112	2455.8	21850.8	4
300	19574.2	.850	.107	1456.6	13674.8	4
300	19574.2	.850	.112	2063.1	18493.6	4
300	30406.5	.850	.102	1441.8	14172.0	4
300	29997.5	.850	.170	1450.3	8524.6	4
300	29690.7	.850	.402	4621.3	11495.5	4
300	30304.3	.850	.148	1398.8	9420.4	4

TABLE 6

VISCOSITY PRESSURE COEFFICIENTS (α)

$$\alpha \equiv \frac{1}{\mu}\frac{\partial u}{\partial p}\bigg|_{p = atm}$$

	$\alpha \times 10^4$ psi^{-1}		
FLUID	100F	210F	300
DN-600	2.0	2.0	2.1
FN-2961	2.4	1.8	1.8
MCS-418	1.7	1.6	1.4
MCS-460	2.3	1.7	1.8

TABLE 7

TRANSITION PRESSURES AND SIGNAL DELAY TIMES OBSERVED
IN PRESSURE VISCOMETER

FLUID	100F	210F	300F
DN-600	90 kpsi: 1/2 sec	90 kpsi: 3/10 sec	90 kpsi: 1/20 sec
FN-2961	40 kpsi: 1/2 sec	60 kpsi: 1 sec	60 kpsi: 1 sec
MCS-418	40 kpsi: 1 sec	40 kpsi: 1/2 sec	50 kpsi: 2 sec
MCS-460	30 kpsi: 3 sec	30 kpsi: 1/2 sec	40 kpsi: 1 sec

TABLE 8

FILM THICKNESS DATA

	Load(lbs)	U(ips)	T_{IN}(°F)	h x 10^6(in)	H_c^* x 10	h_m x 10^6(in)
FN2961	14.93	13.7	74.1	9.75	15.6	3.55
	14.93	27.4	74.2	12.88	20.3	7.11
	14.93	54.9	74.1	16.88	27	9.77
	1.99	13.7	75.6	17.31	27.7	13.78
	1.99	27.4	75.6	22.8	36.5	16.88
	1.99	54.9	75.6	29.4	47	23.11
MCS460	14.95	13.7	73.5	5.24	8.4	1.75
	15.1	27.4	73.5	7.78	12.4	3.49
	15.3	54.9	73.5	10.48	16.8	5.24
	1.99	13.7	73	9.6	15.35	5.24
	1.99	27.4	72.9	13.88	22.2	8.47
	1.91	54.9	72.9	20.95	33.5	14.85
MCS418	14.95	13.7	73.8	3.93	6.3	1.57
	14.95	27.4	73.8	5.89	9.43	2.36
	14.95	54.9	73.8	8.63	13.8	3.14
	1.99	13.7	73.5	5.1	8.15	3.14
	1.99	27.4	73.7	7.46	11.9	4.71
	1.99	54.9	73.8	11	17.6	7.86
DN600	14.75	13.7	73.7	2.66	4.25	1.77
	15.5	27.4	73.8	4.43	7.1	2.66
	15.1	54.9	73.8	7.55	12.1	3.54
	1.99	13.7	73.8	3.54	5.83	1.77
	1.99	27.4	73.8	6.2	9.9	3.54
	1.99	54.9	73.8	9.75	15.6	7.09

$h_c \equiv$ film thickness at center of contact

$h_m \equiv$ minimum film thickness in contact

$H_c^* \equiv \frac{h_c}{R}$ where R = 0.625"

$T_{IN} \equiv$ inlet fluid temperature °F

U $\equiv$ surface velocity of sphere

TABLE 9

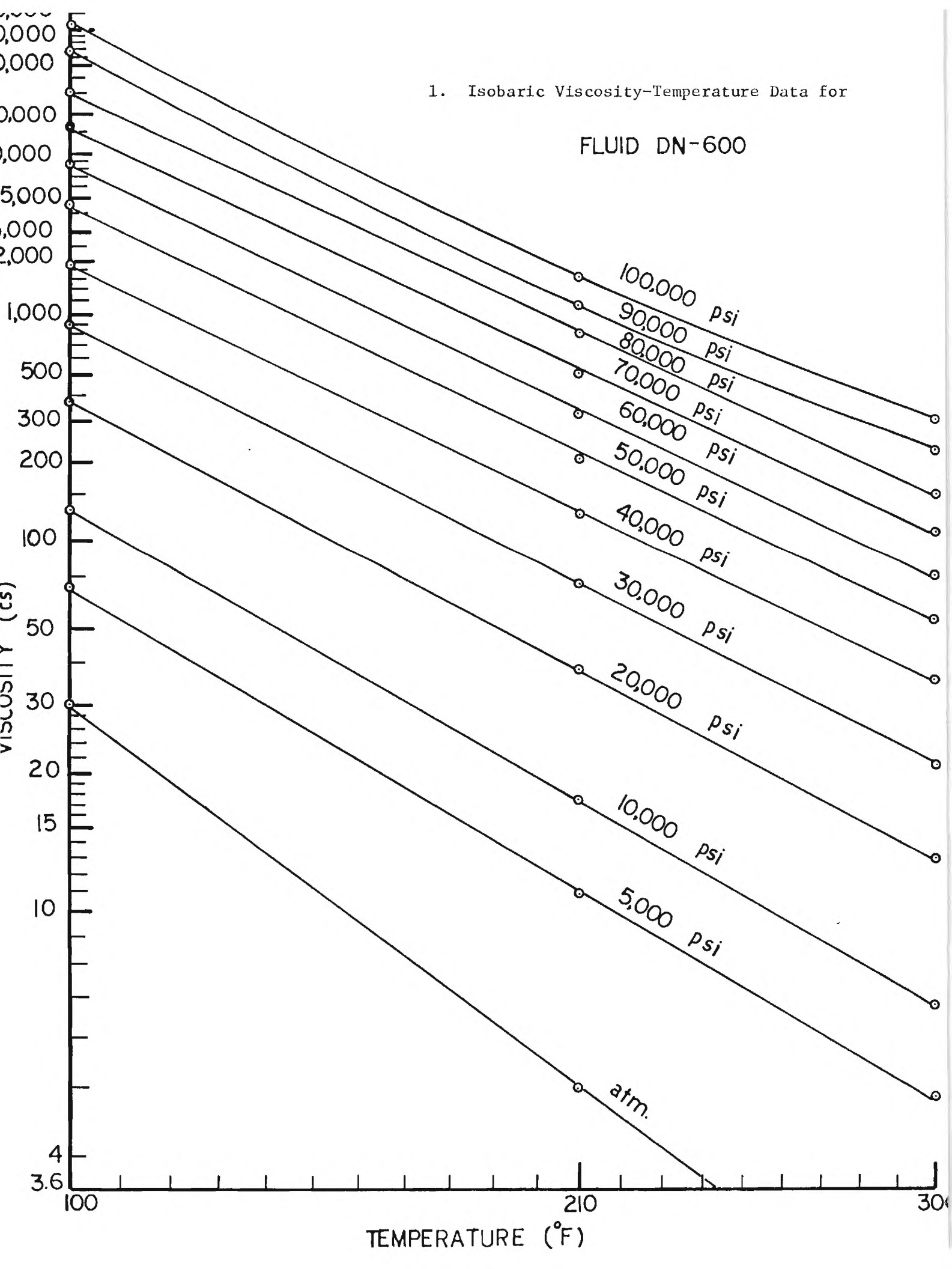
TRACTION COEFFICIENT, [TC]

	Normal Load (lbs)	1	2	5	15
	Max. Hertzian Stress x 10^{-3}(psi)	60	75	102	148
	Mean Hertzian Stress x 10^{-3}(psi)	40	50	68	99
Fluids	Sliding Velocity (ips)	TC x 10^{+2}			
FN2961	13.7	5.35	6.5	7.2	7.3
	27.4	4.4	5.4	6.4	6.7
	54.9	3.88	4.6	5	5.2
MC S460	13.7	8.65	9.9	10.05	10.05
	27.4	6.4	8.4	9.6	9.5
	54.9	4.5	6.5	7.5	7.4
MCS418	13.7	6.3	7.4	8	7.8
	27.4	5.6	6.65	7.2	7.2
	54.9	3.85	5.4	5.8	5.8
DN600	13.7	3.5	4.4	5.1	5
	27.4	3	4.05	4.6	4.25
	54.9	2.5	3.5	3.95	3.8

$$TC \equiv \frac{\text{TRACTIVE FORCE AT CONTACT}}{\text{LOAD ON CONTACT}}$$

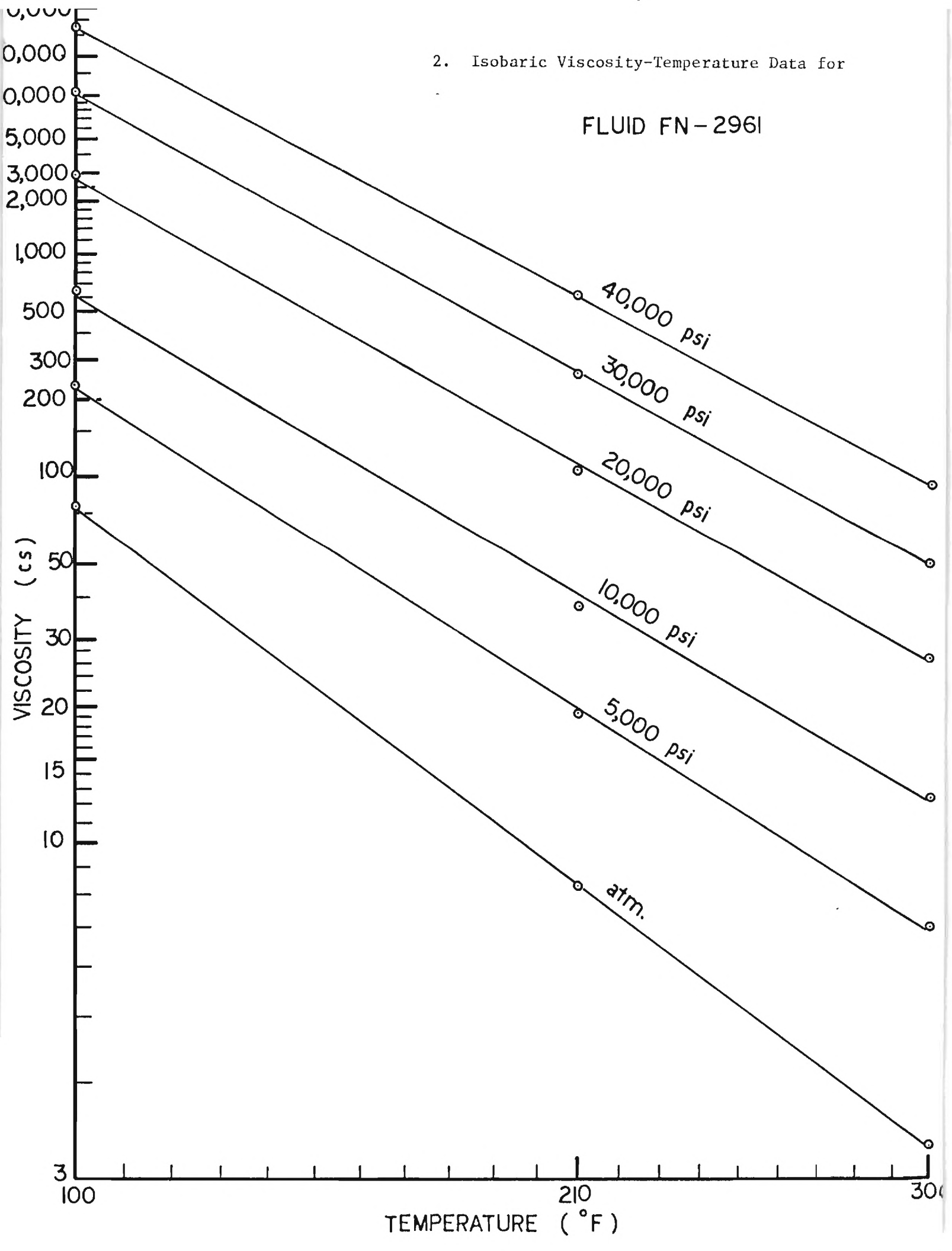
1. Isobaric Viscosity-Temperature Data for

FLUID DN-600



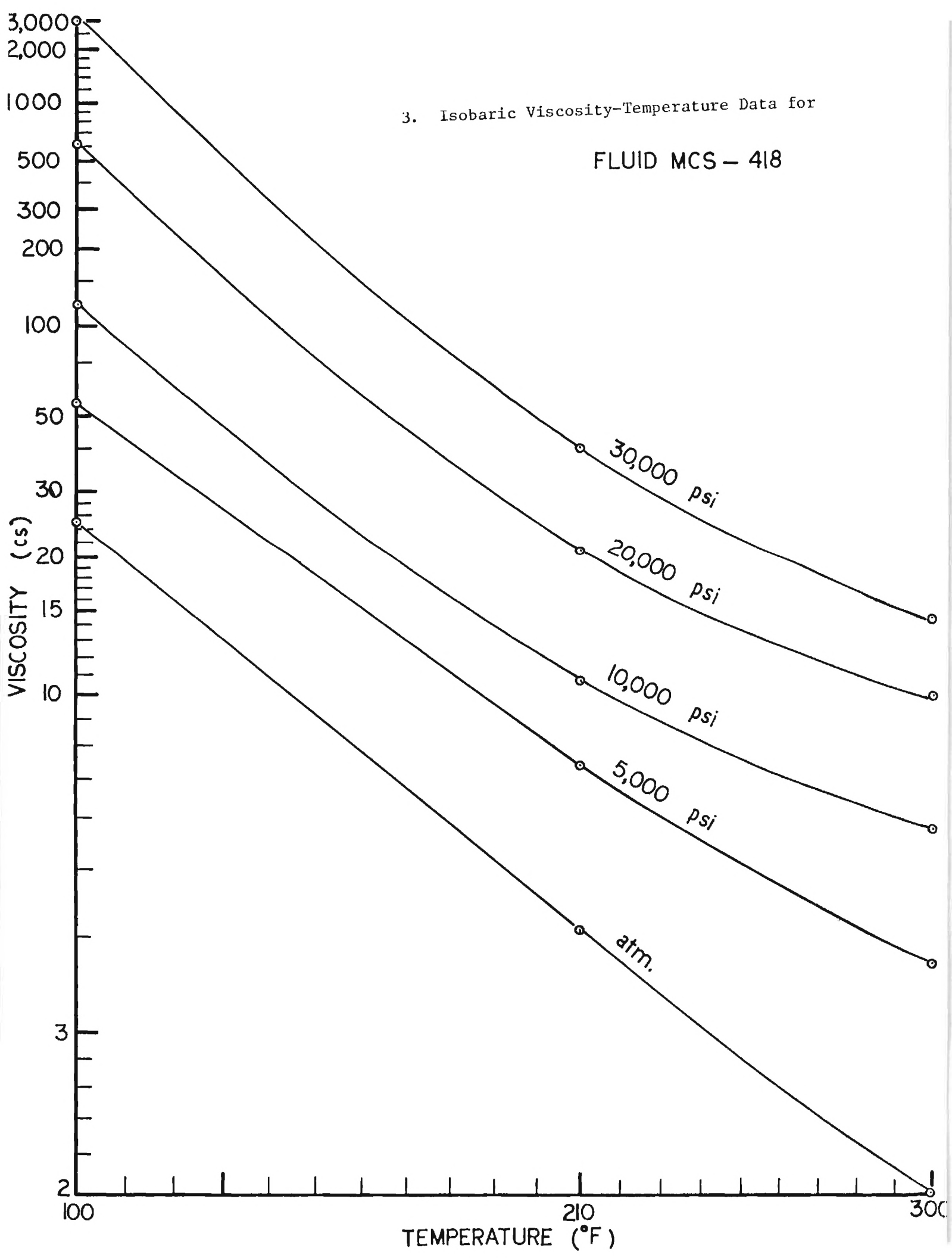
2. Isobaric Viscosity-Temperature Data for

FLUID FN-2961



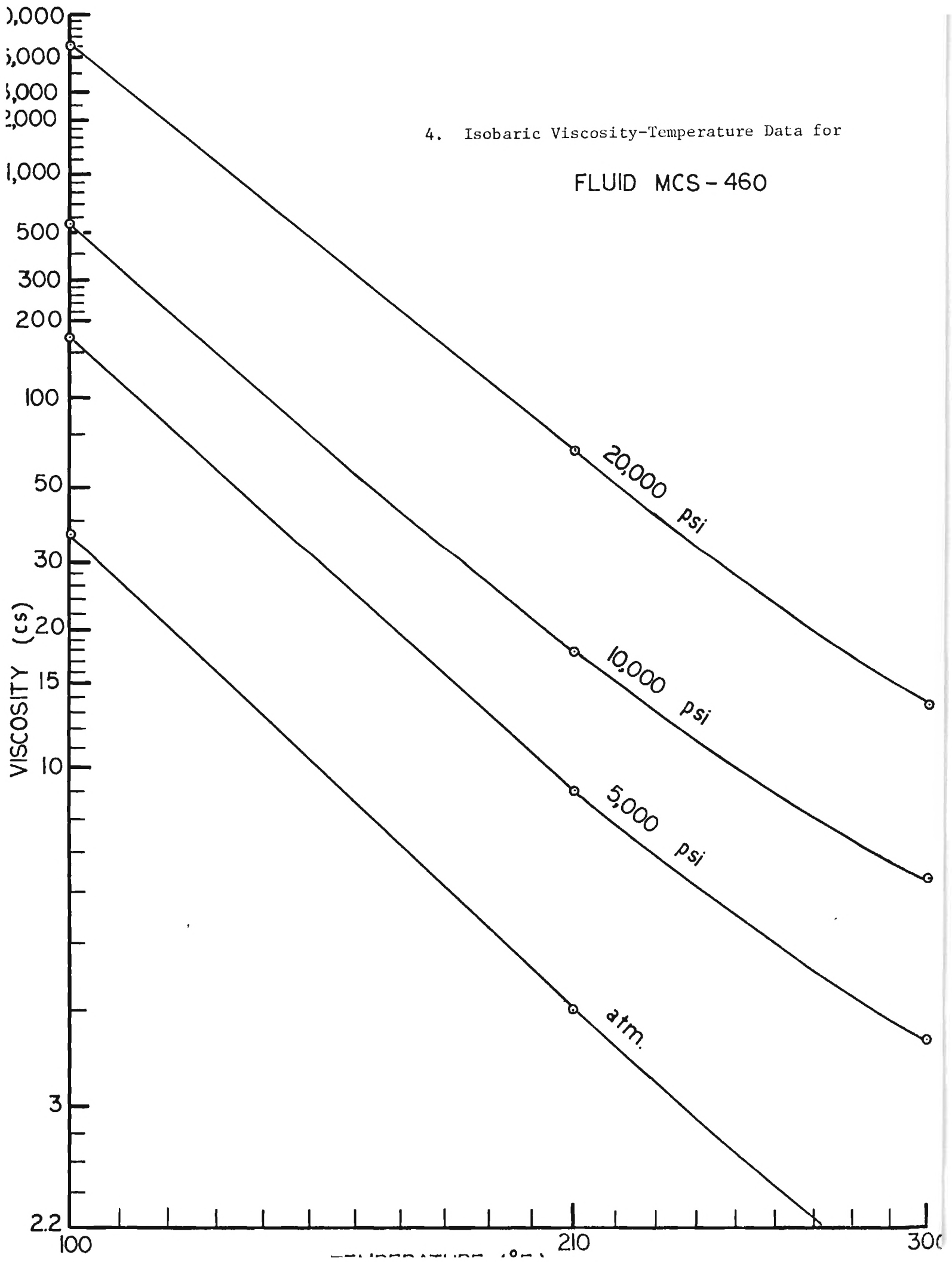
3. Isobaric Viscosity-Temperature Data for

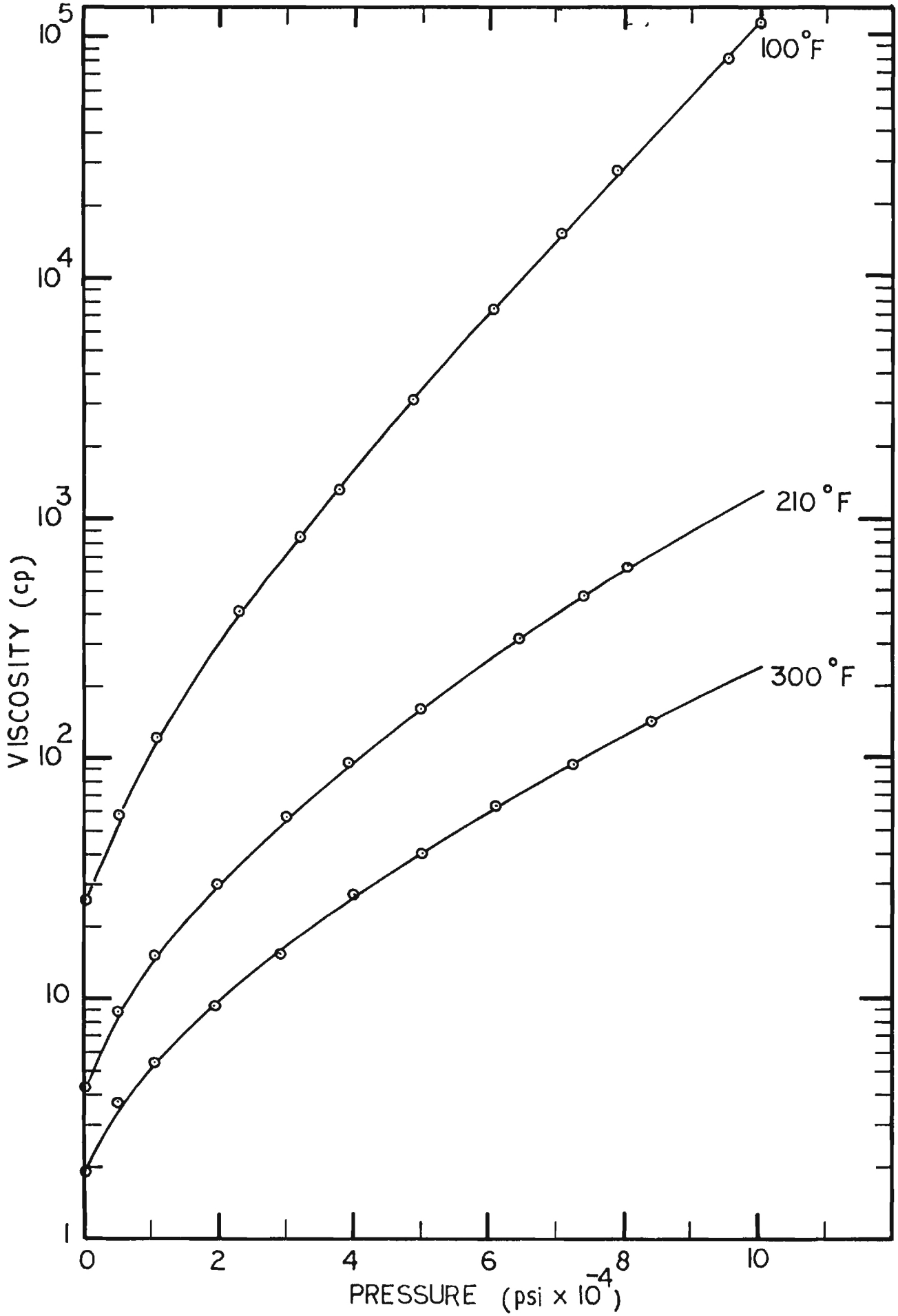
FLUID MCS – 418



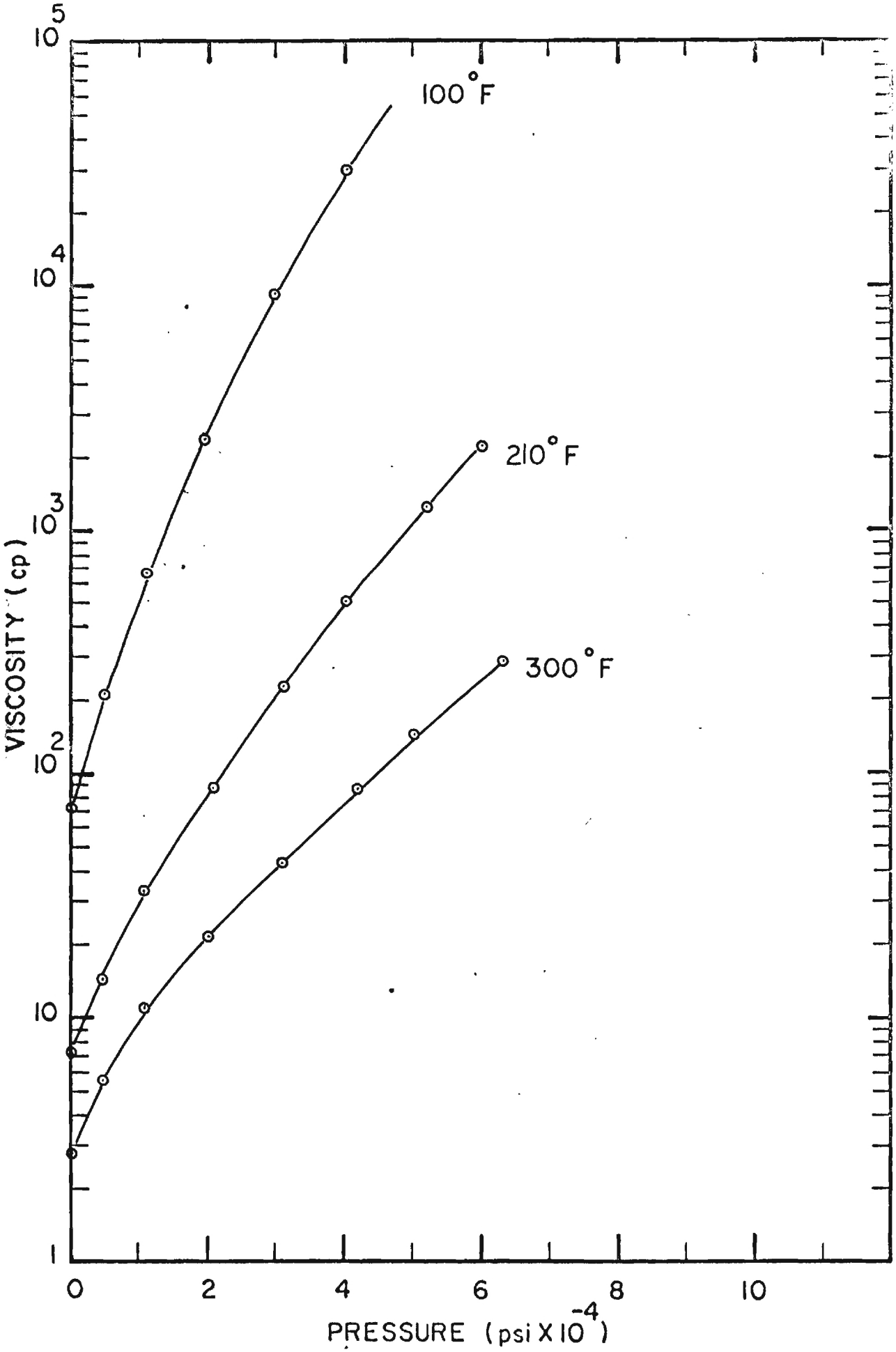
4. Isobaric Viscosity-Temperature Data for

FLUID MCS-460

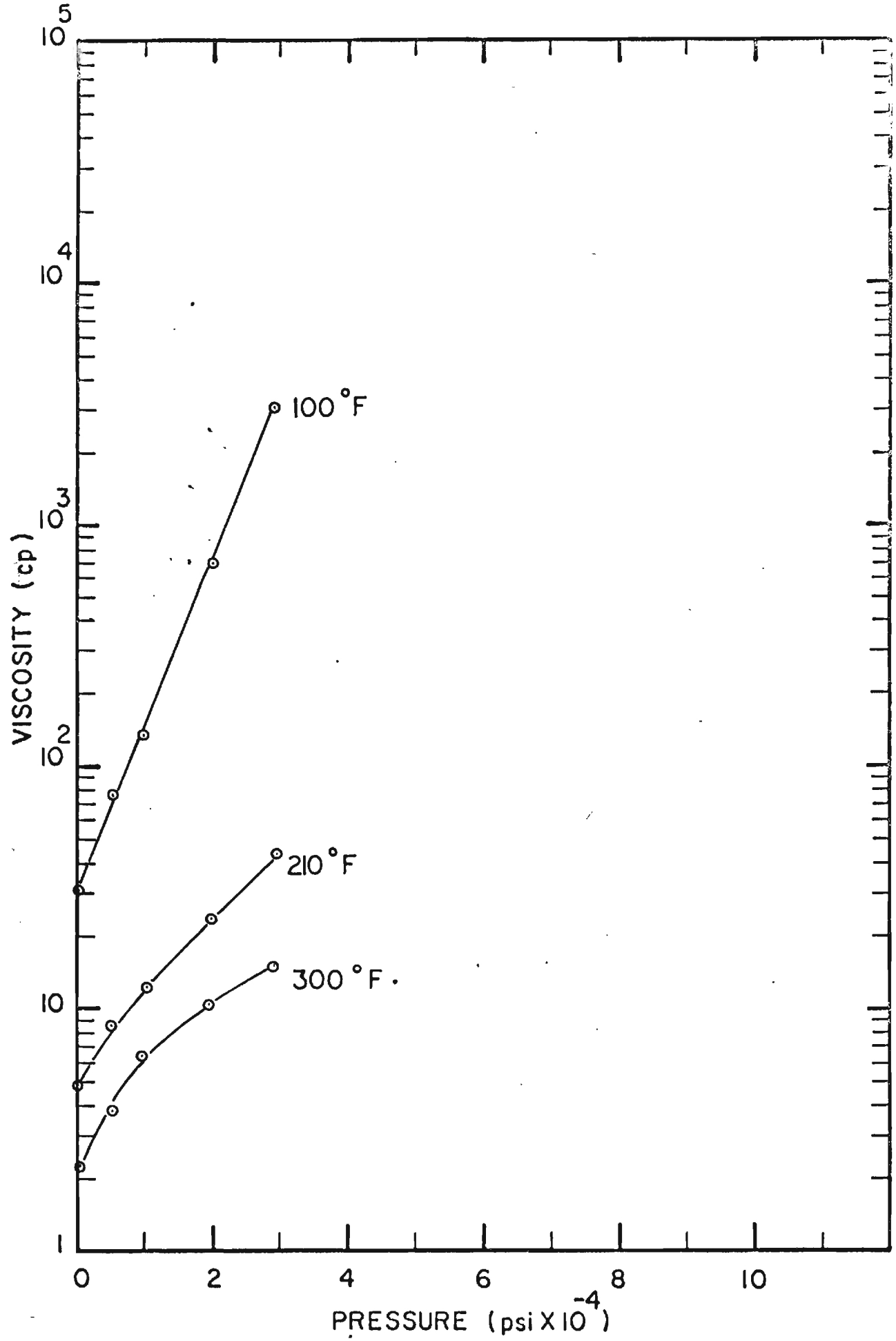




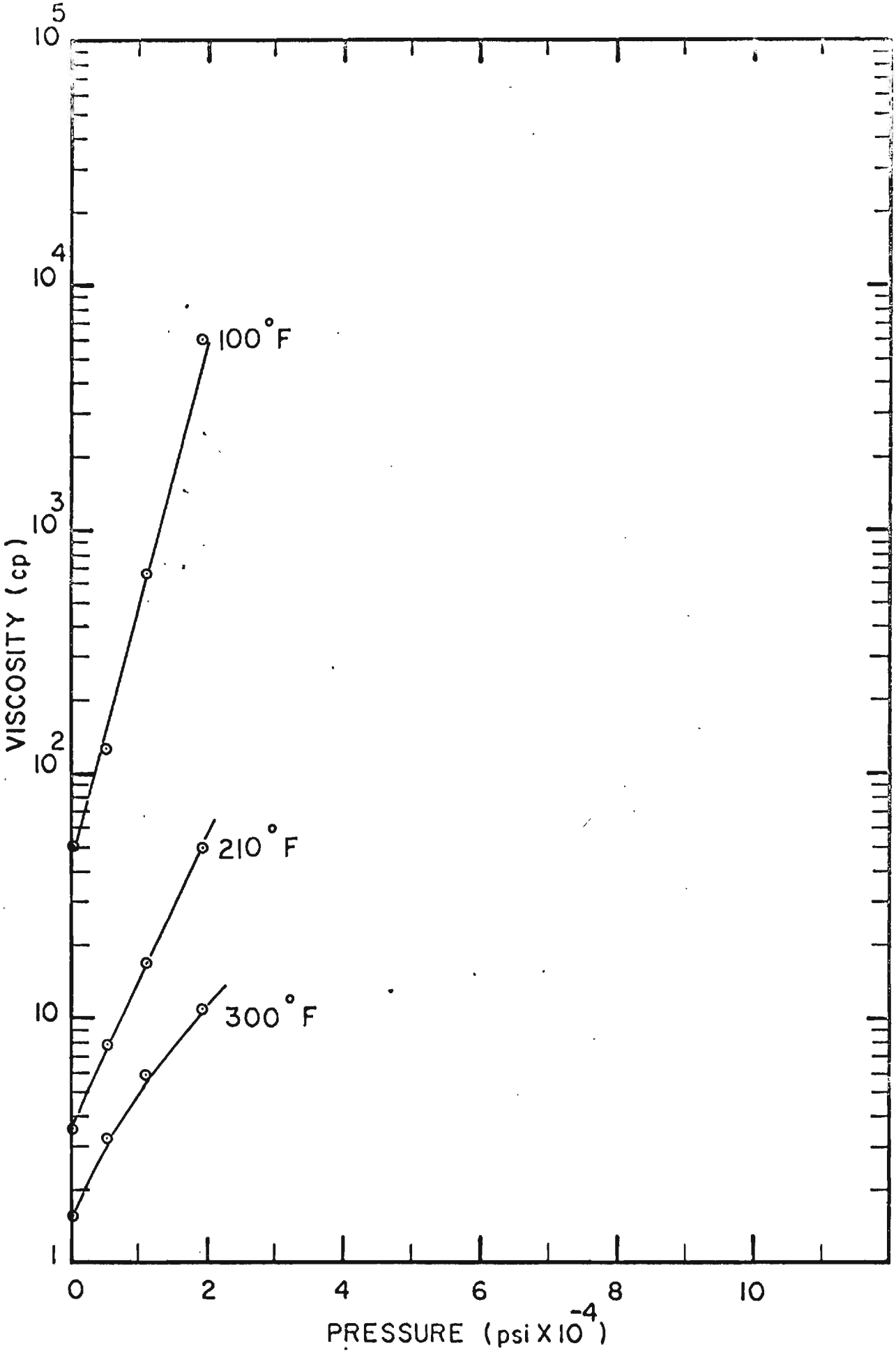
5. Viscosity–Pressure Relation for Fluid DN-600



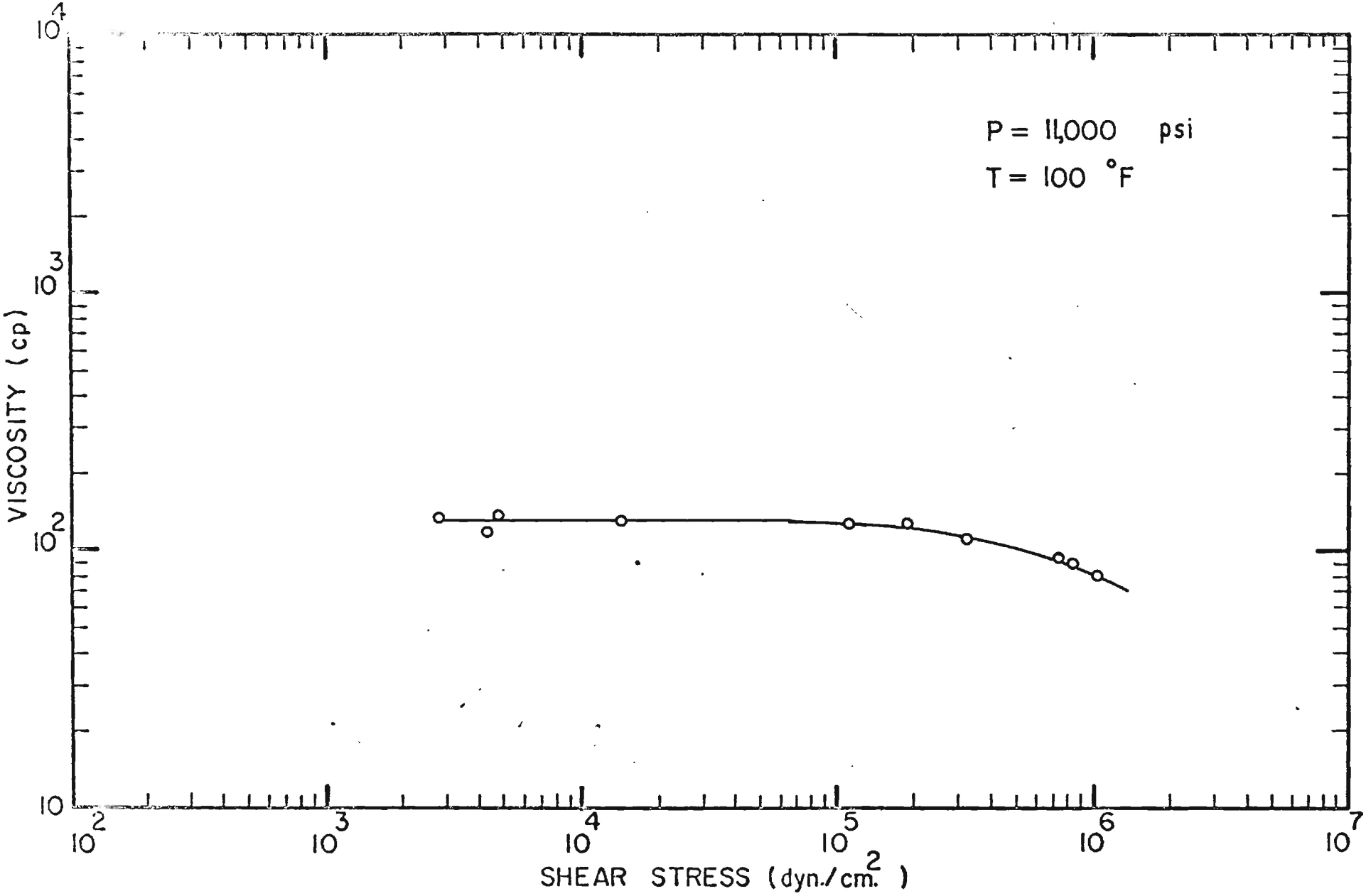
6. Viscosity–Pressure Relation for Fluid FN-2961



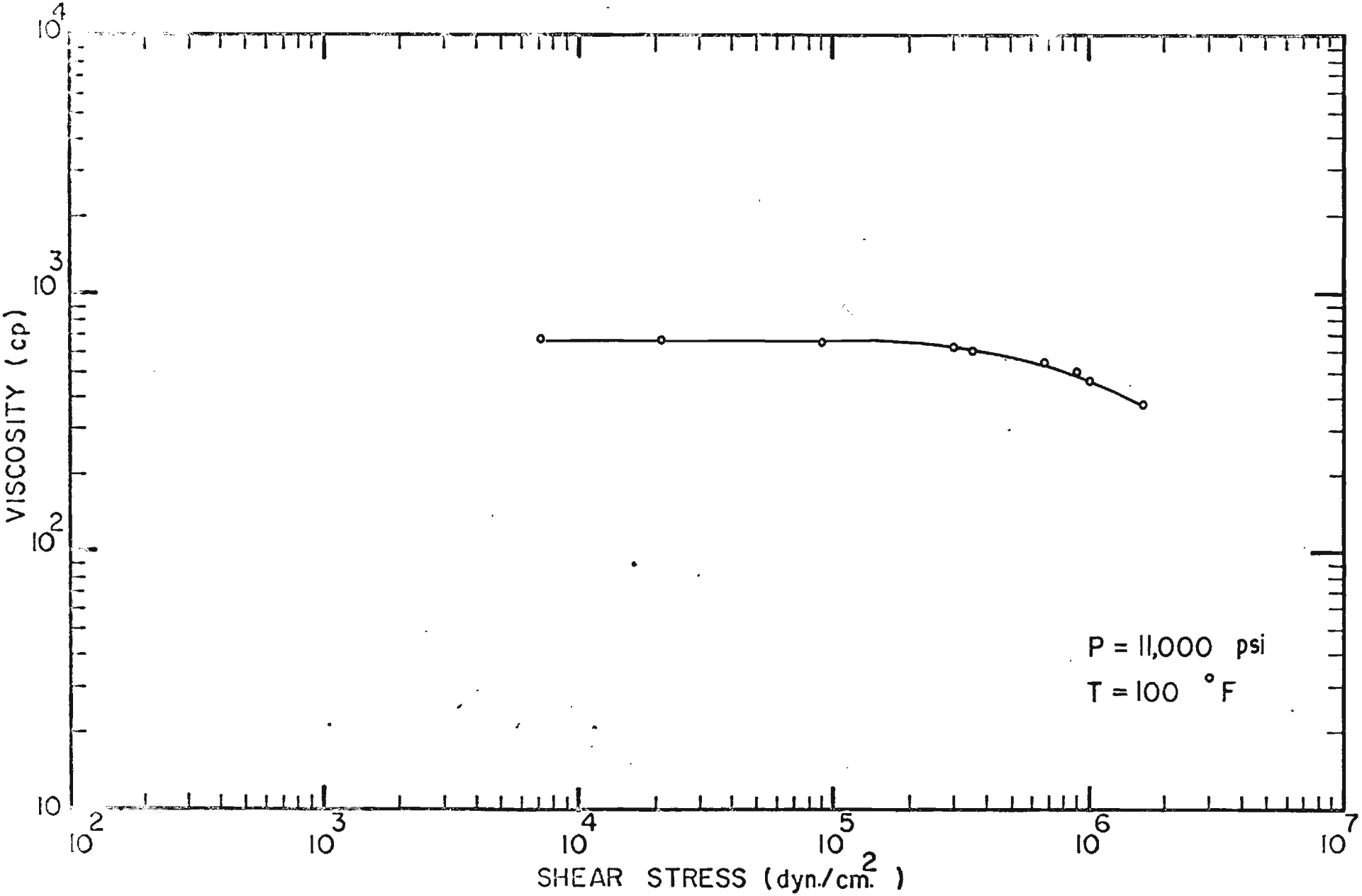
7. Viscosity_Pressure Relation for Fluid MCS-418



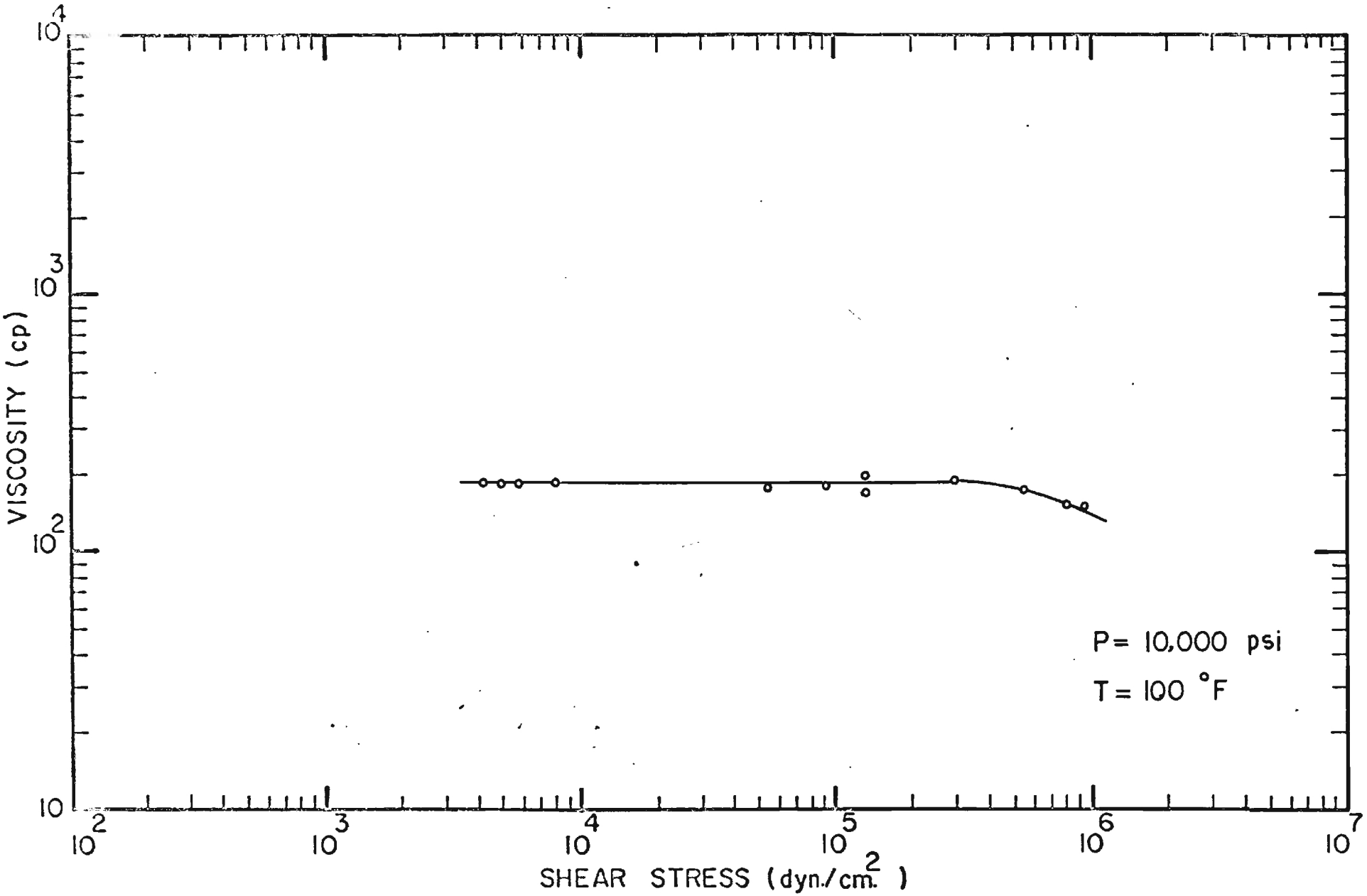
8. Viscosity_Pressure Relation for Fluid MCS-460



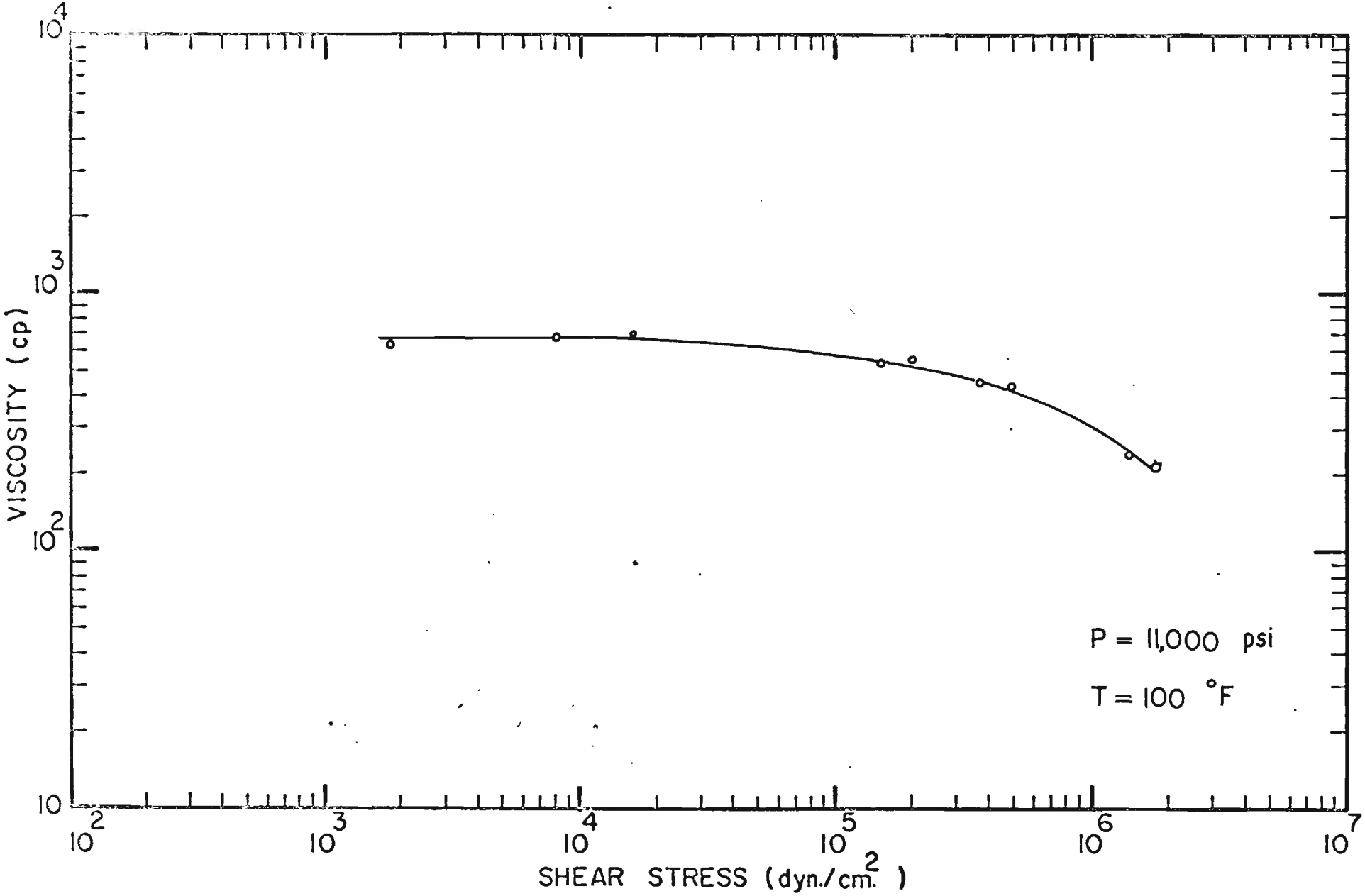
9. Viscosity-Shear Stress Relation for Fluid DN-600



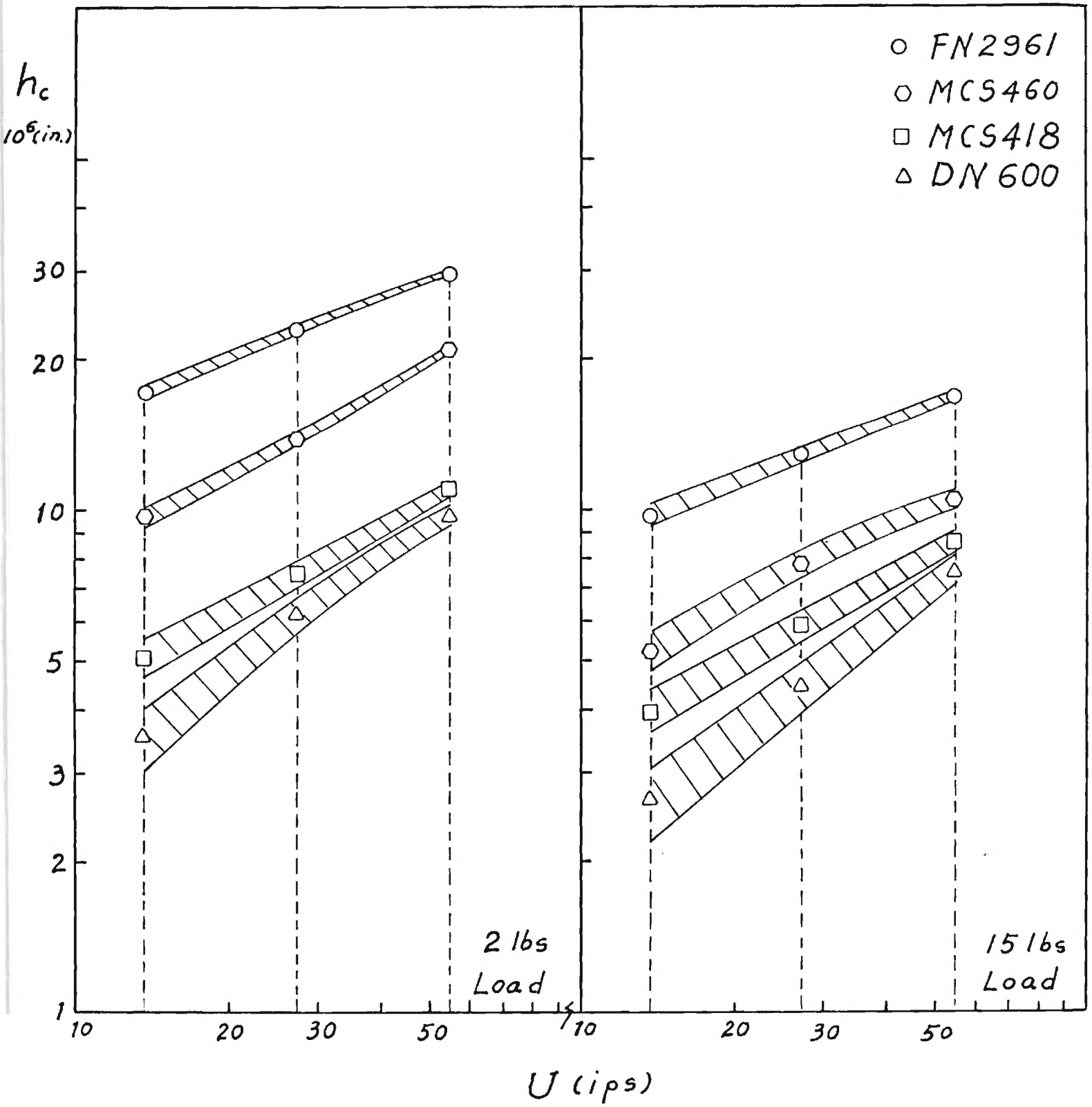
10 Viscosity-Shear Stress Relation for Fluid FN-2961



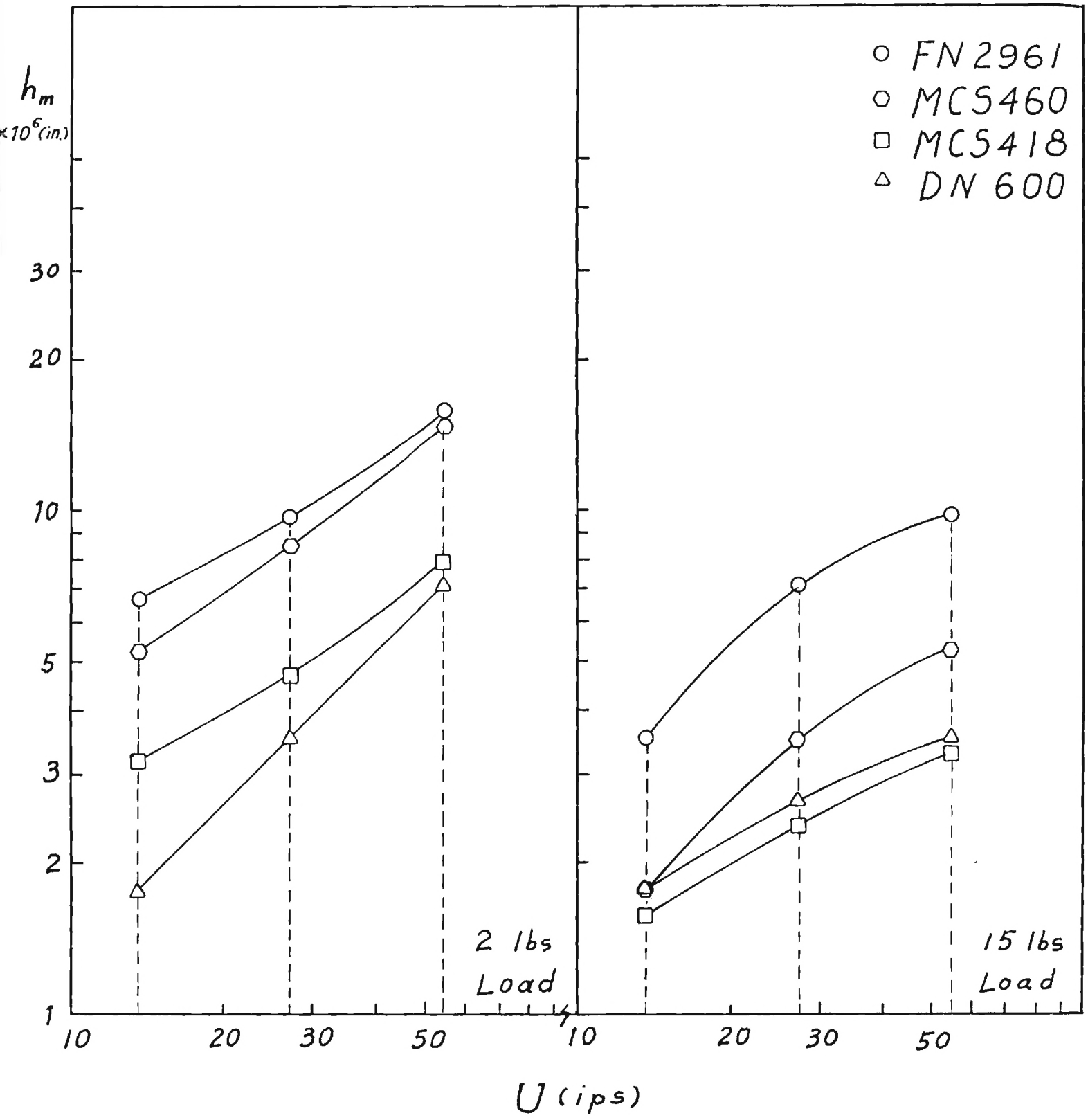
II. Viscosity-Shear Stress Relation for Fluid MCS-418



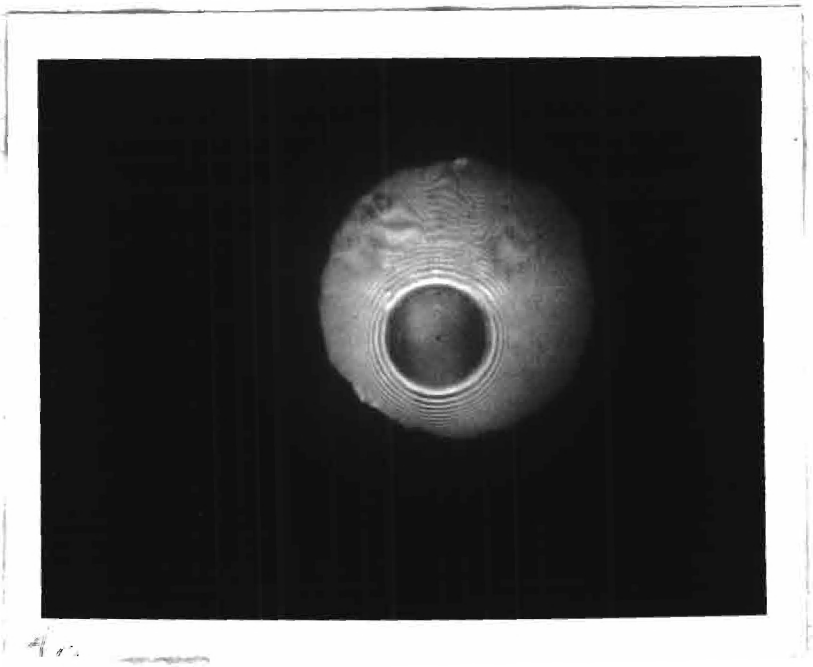
12. Viscosity-Shear Stress Relation for Fluid MCS-460

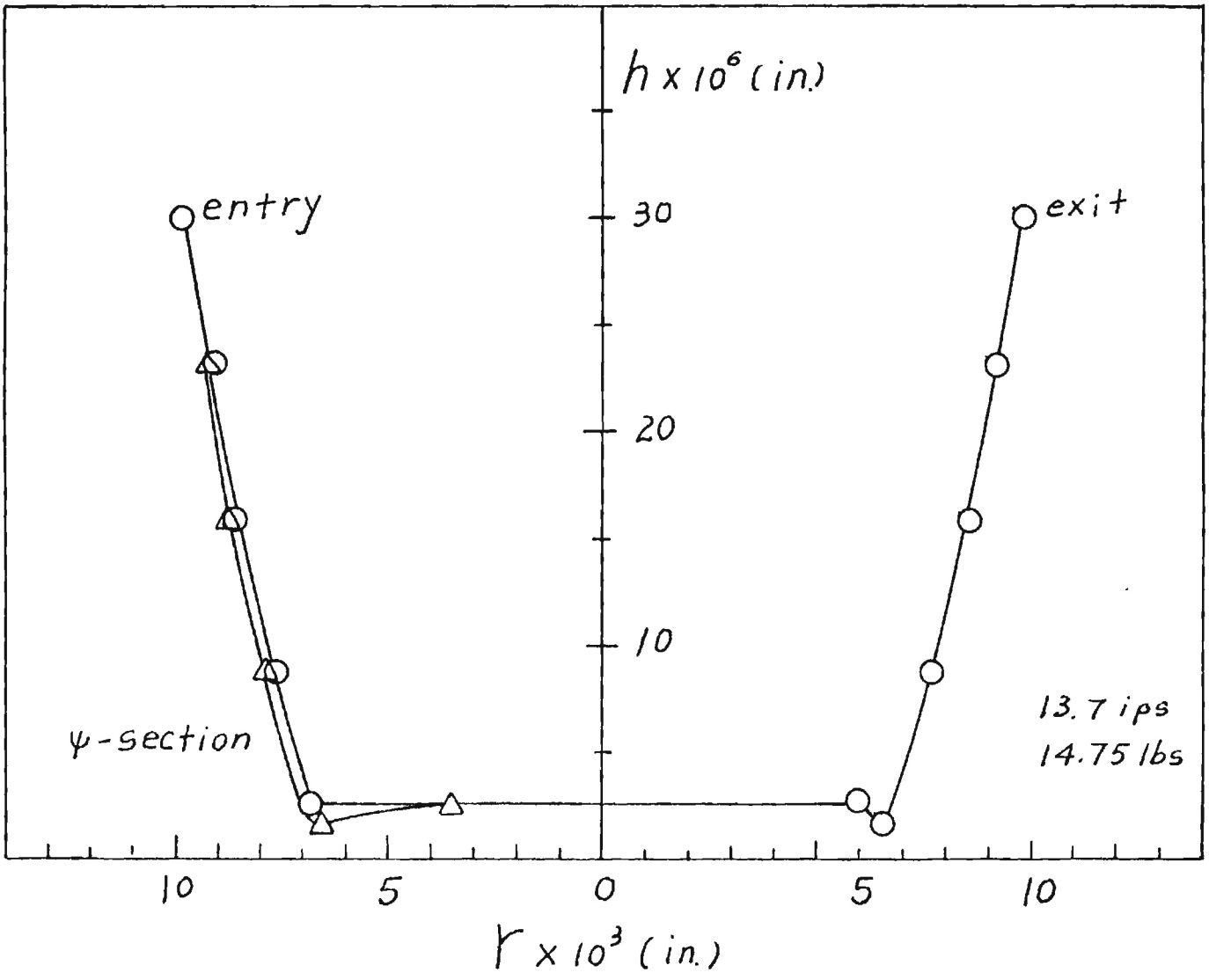


13. Centerline Film Thickness

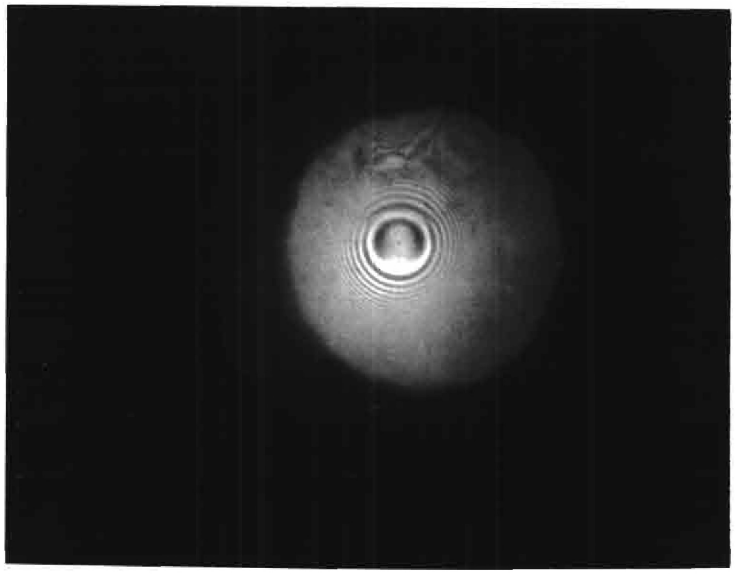


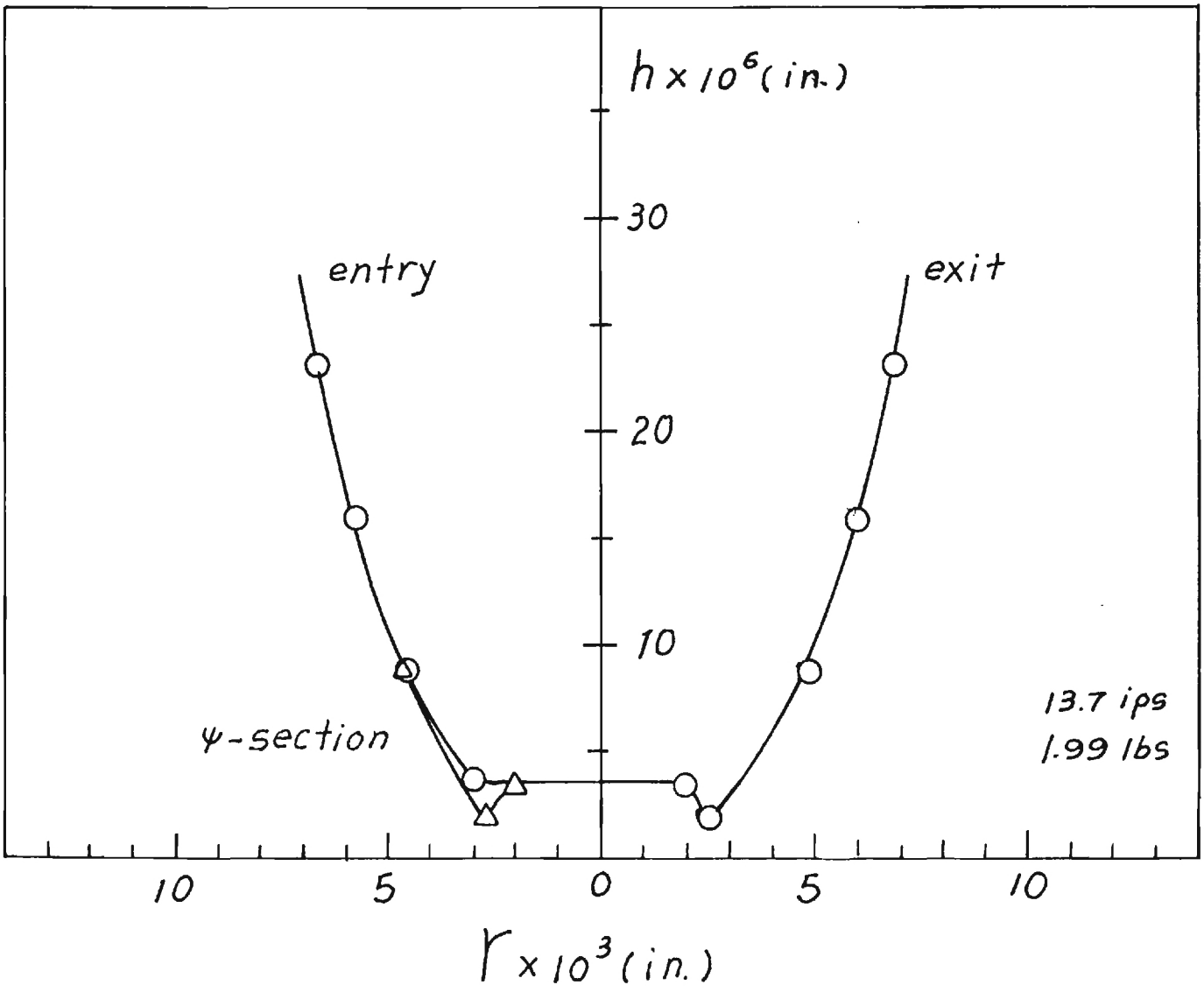
14. Minimum Film Thickness



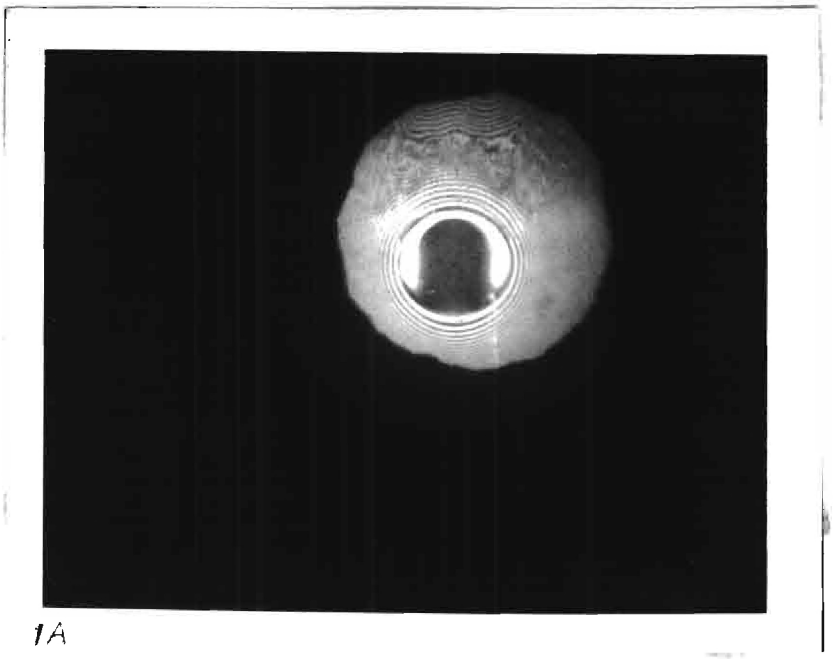


15A. Film Thickness Profile (D N 600)

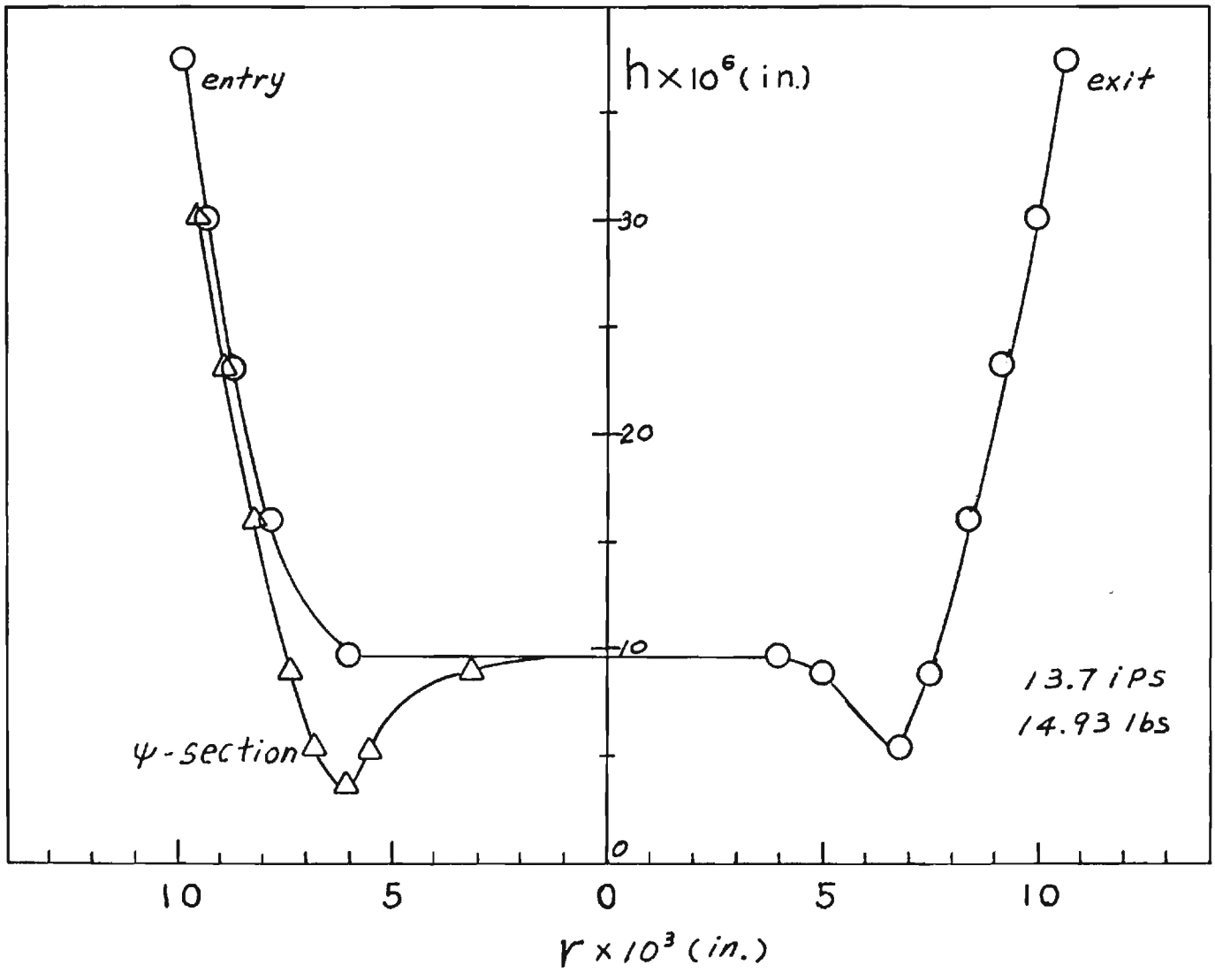




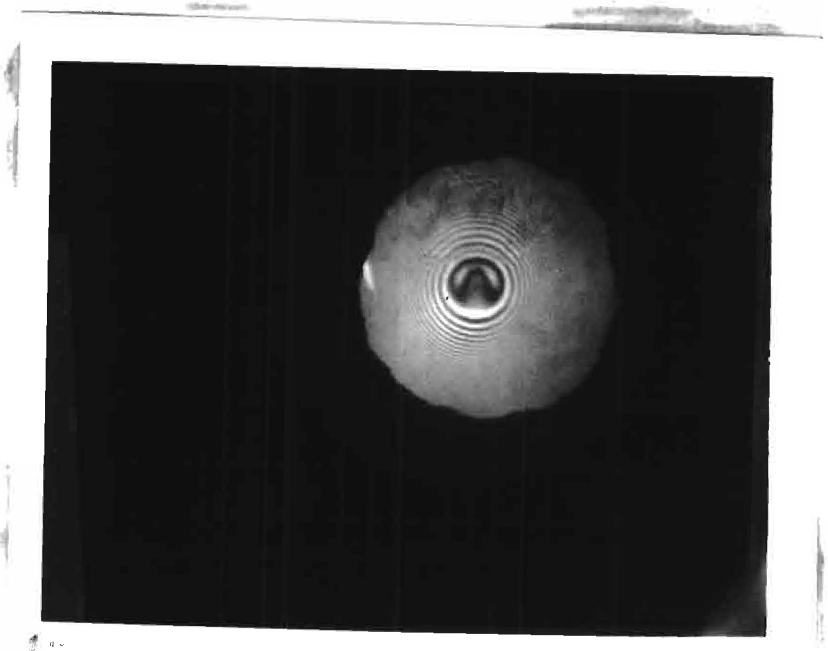
15B. Film Thickness Profile (DN 600)

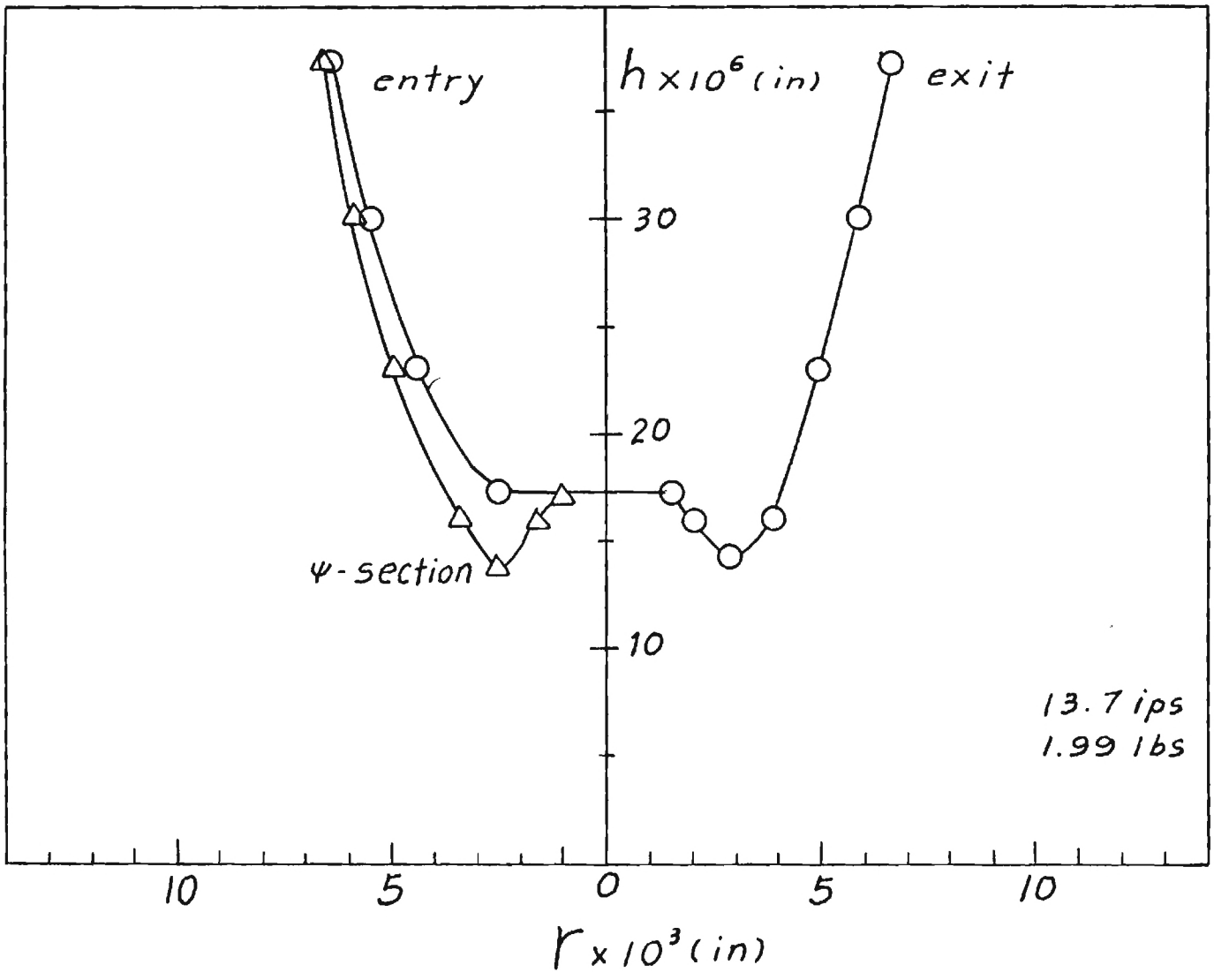


1A

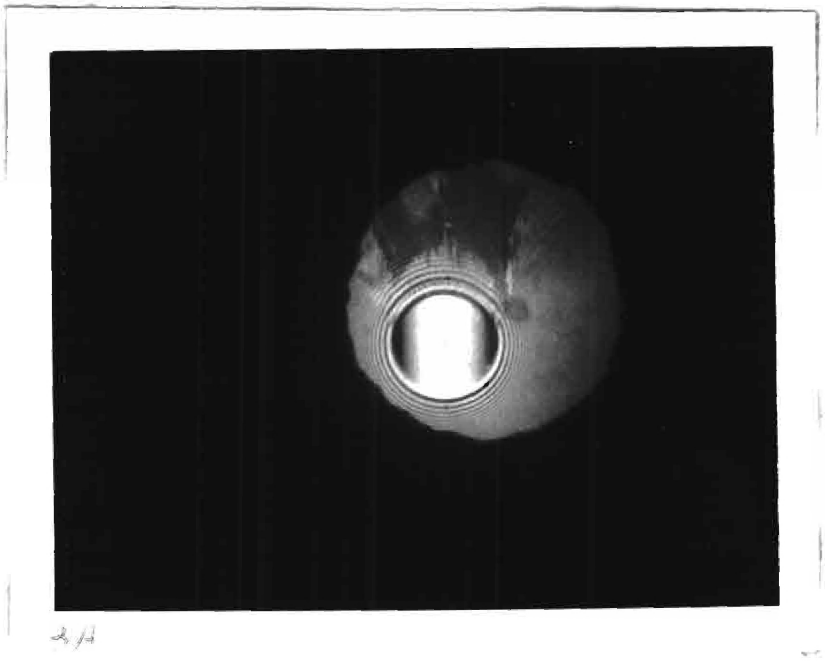


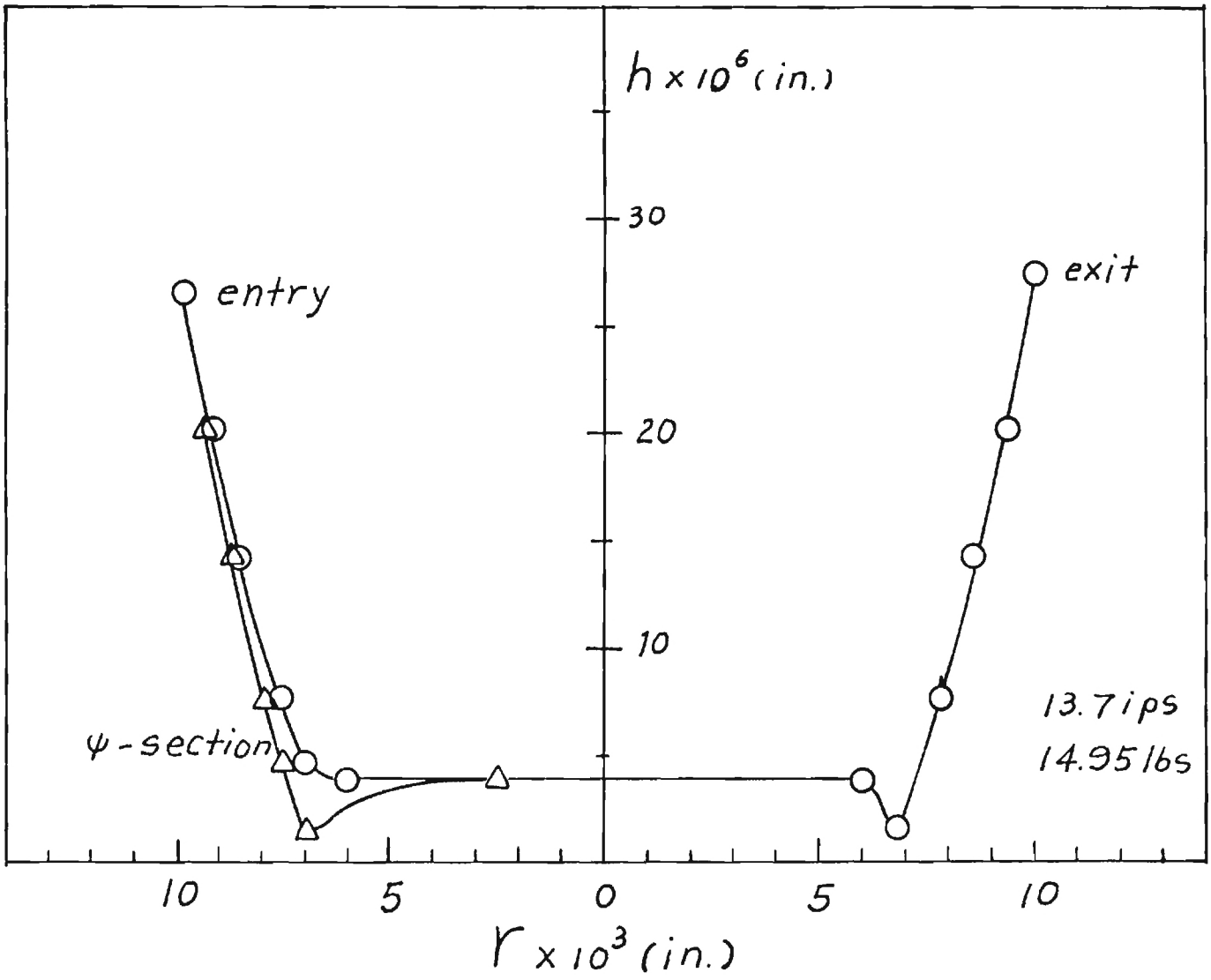
16A. Film Thickness Profile (FN2961)



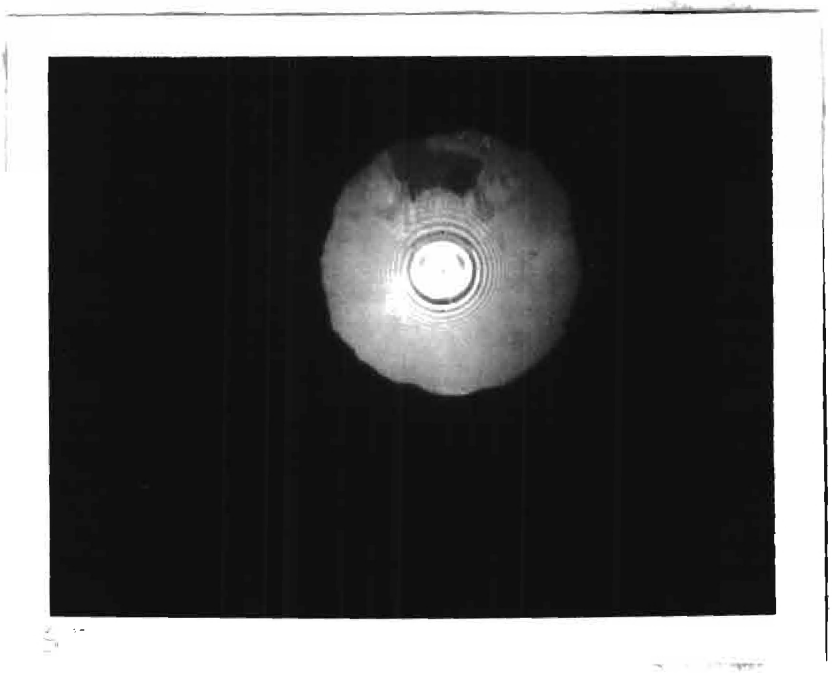


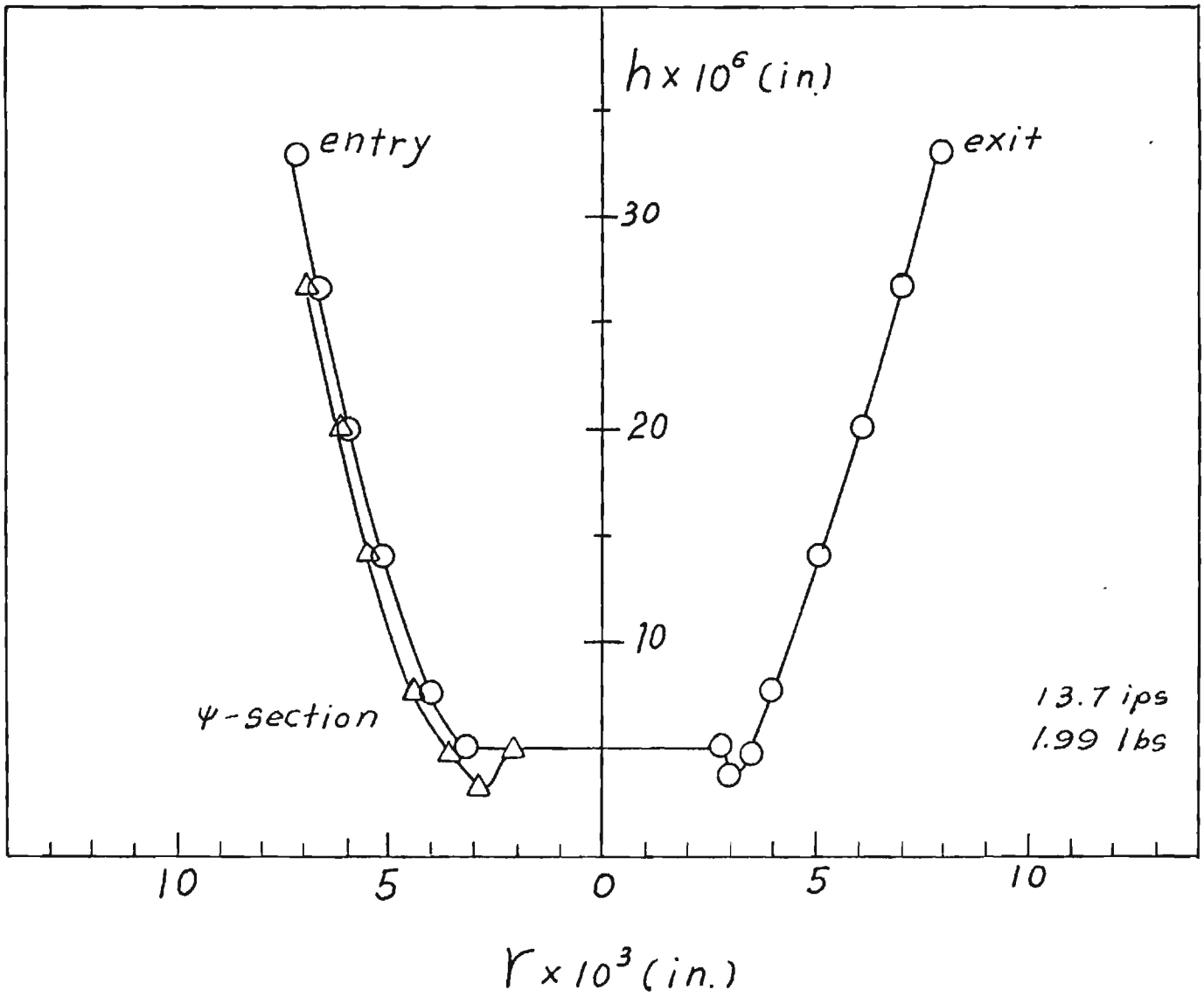
16B. Film Thickness Profile (FN2961)



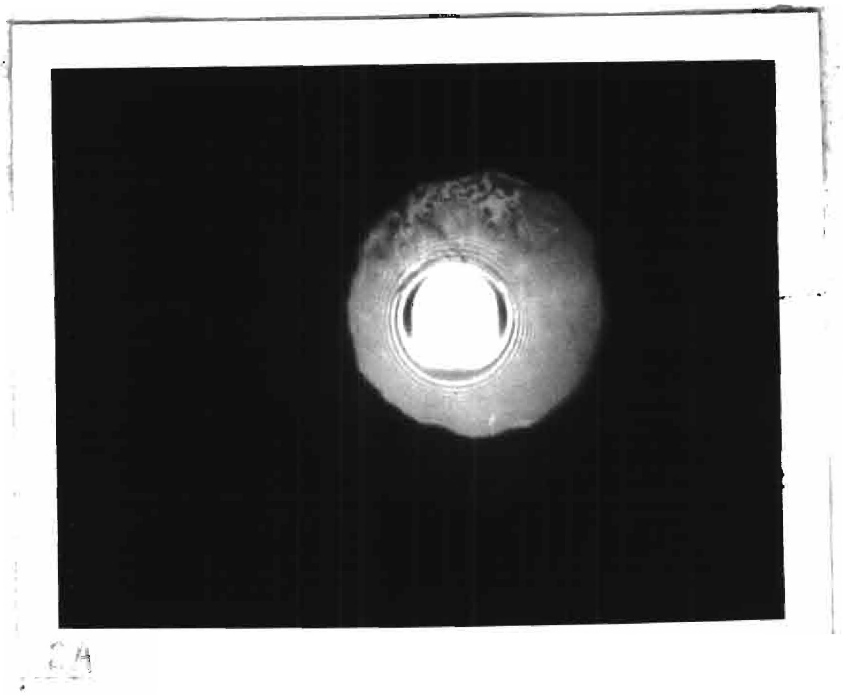


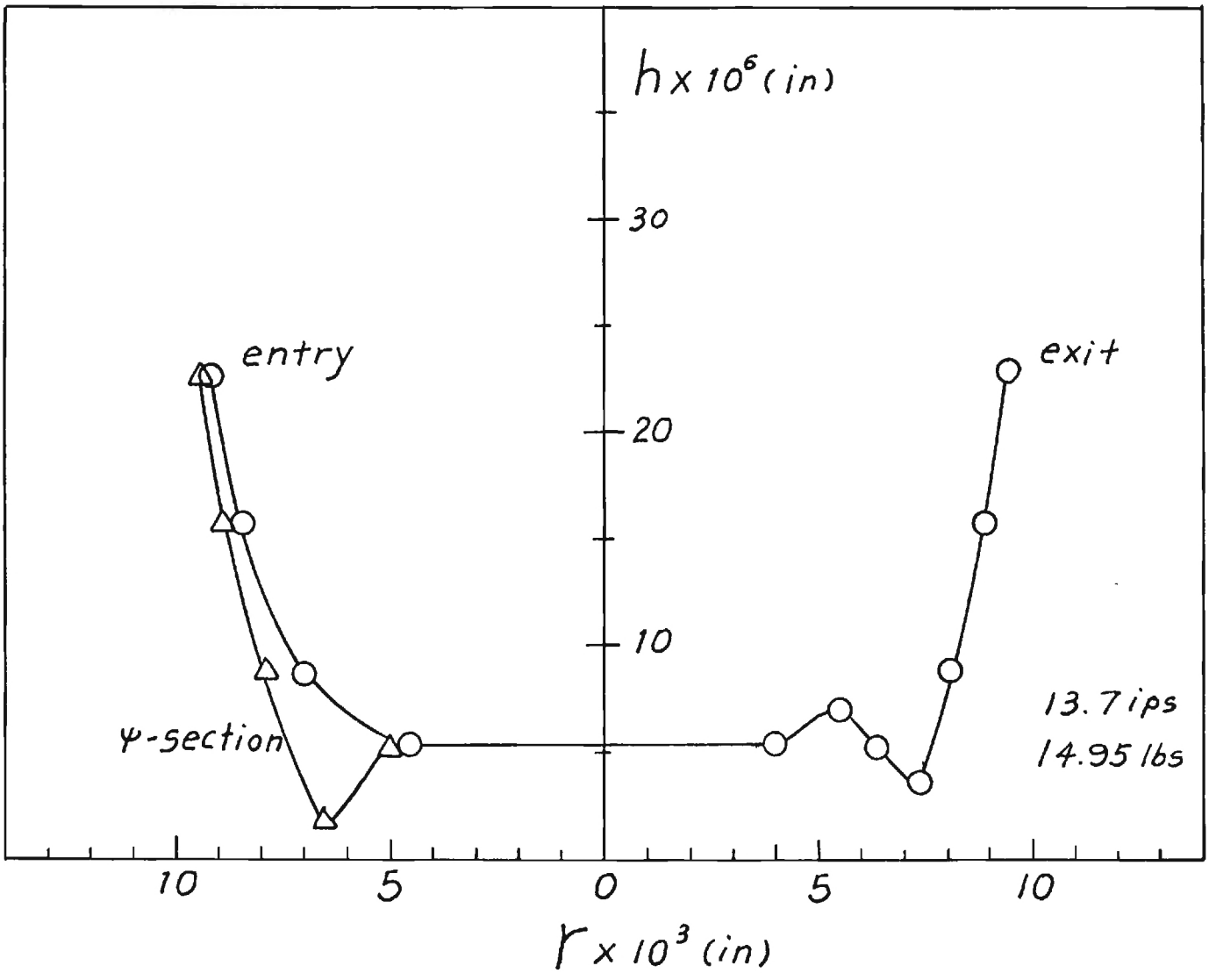
17A. Film Thickness Profile (MCS418)



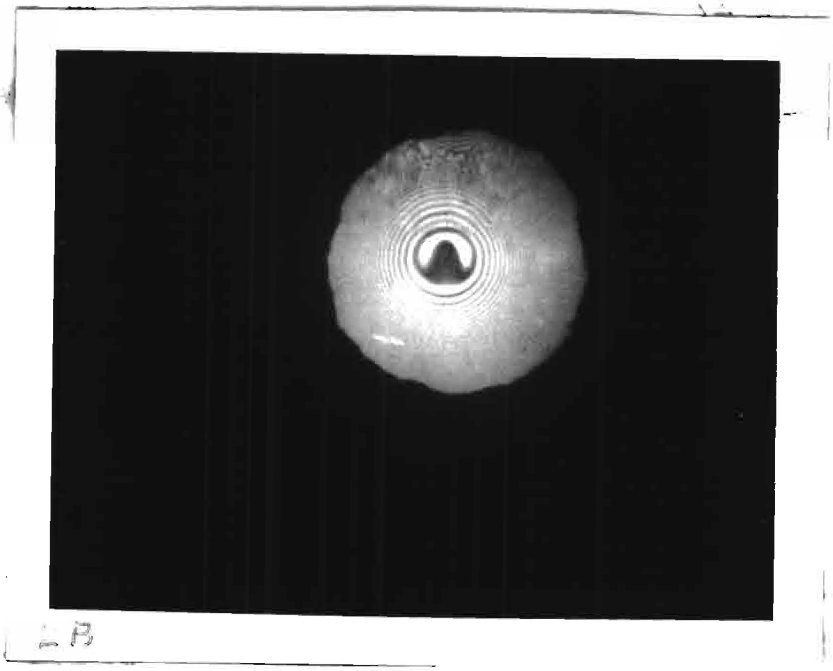


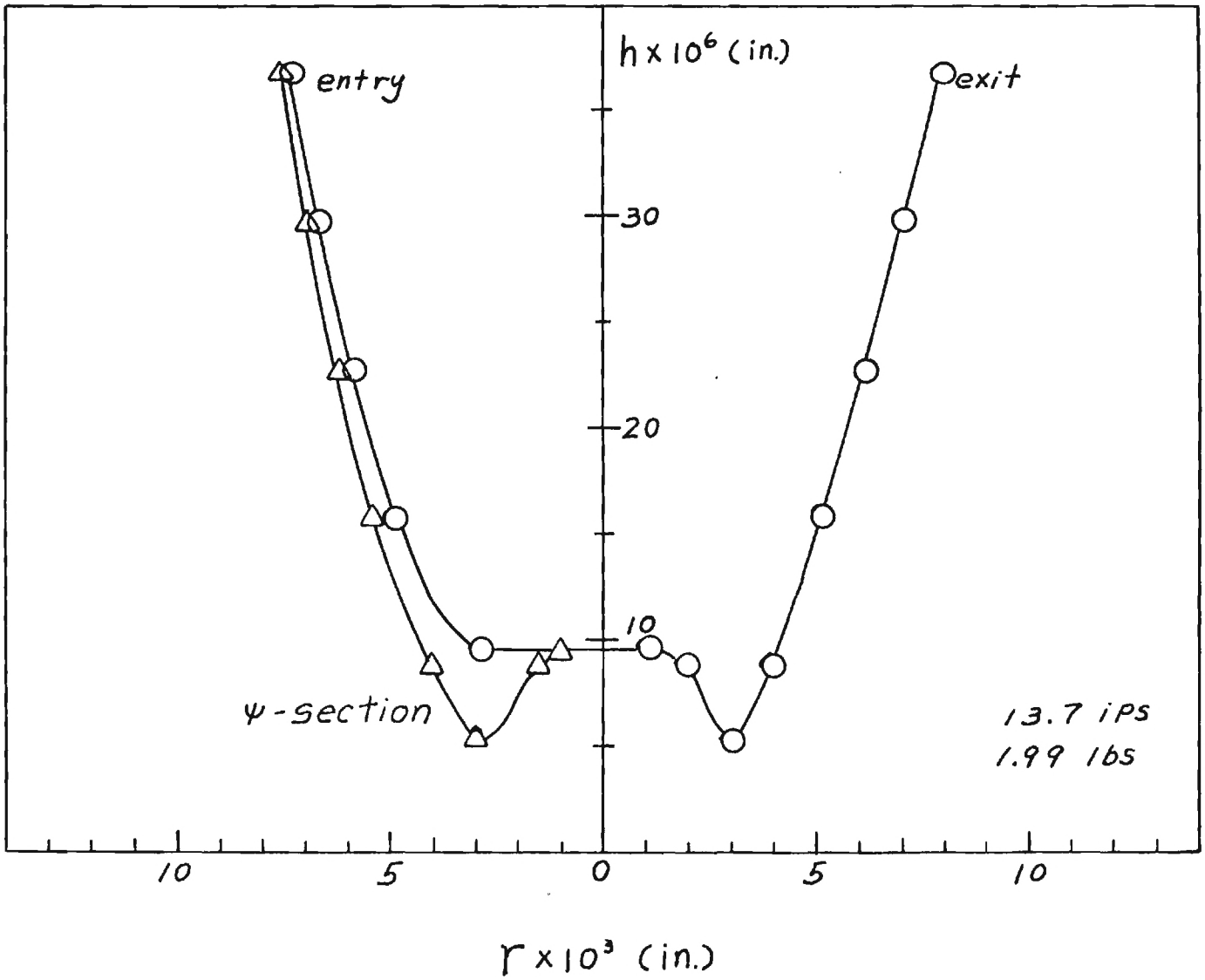
17B. Film Thickness Profile (MCS 418)



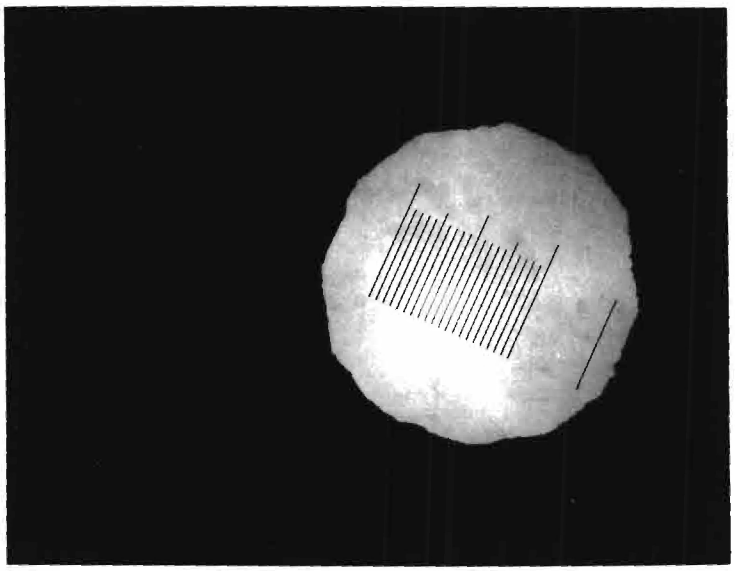


18A. Film Thickness Profile (MCS 460)

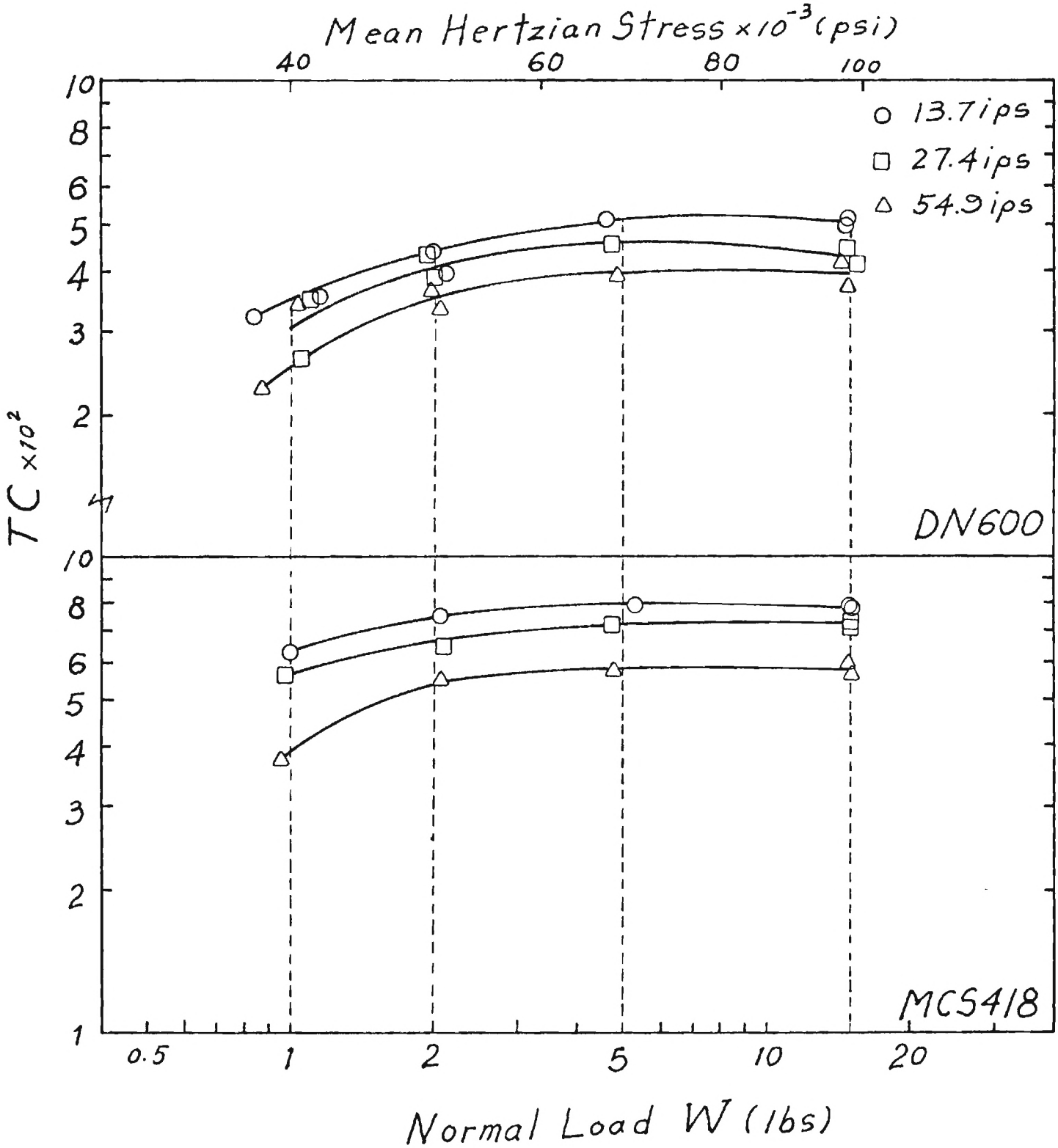




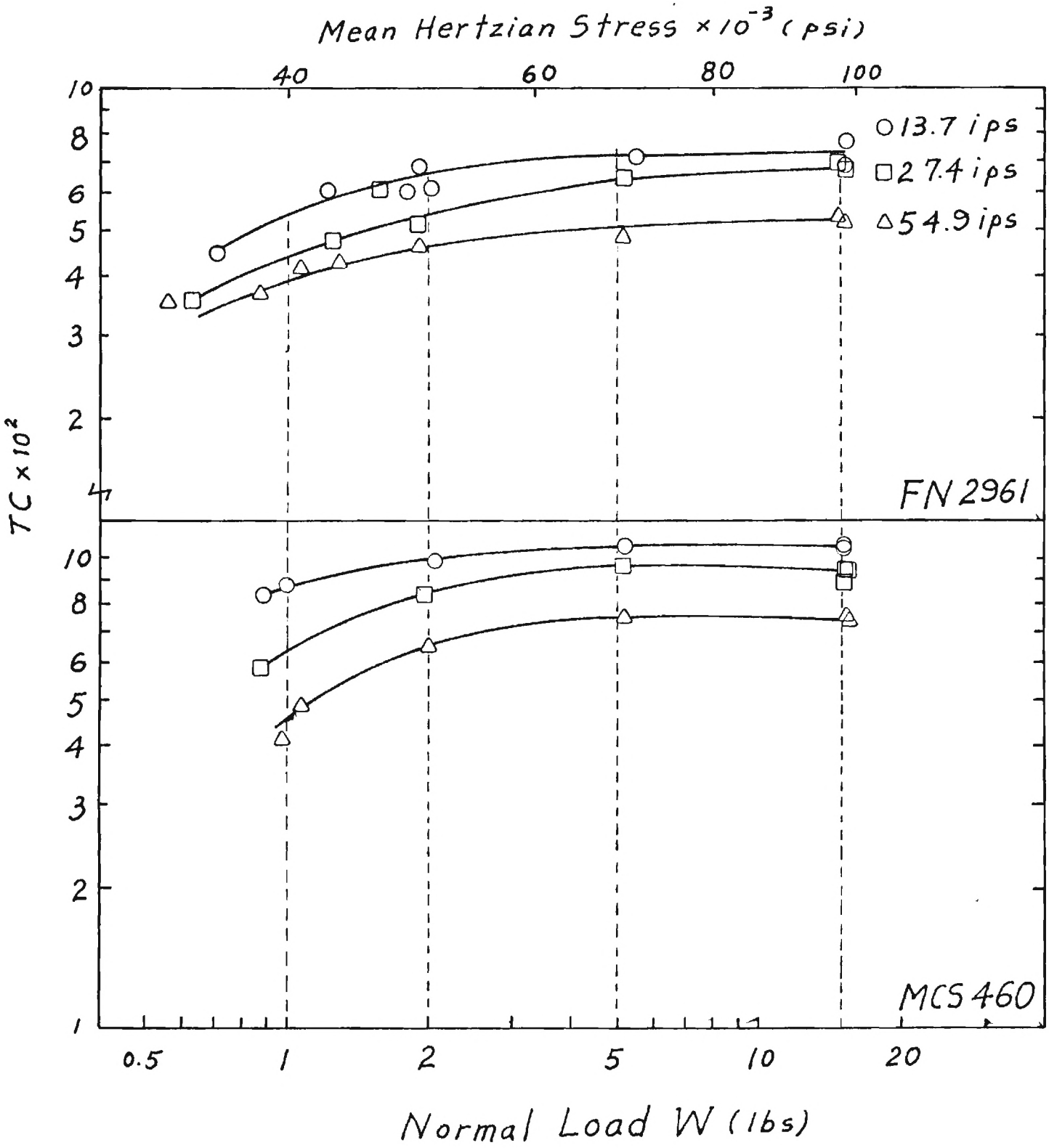
18B Film Thickness Profile (MCS460)



19. Stage Micrometer Photograph
(each small division is 1×10^{-3} inches)



20. Traction Coefficient



21. Traction Coefficient